Worldwide

Basic Study on Reinforcement Measures for Local Natural Geomaterials and Problematic Soil Measures Encountered in Construction Works in Developing Countries

Handbook for Problematic Soil Measures

May 2025

Japan International Cooperation Agency (JICA)

Nippon Koei Co., Ltd.

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Preface

Last year marked the 70th anniversary of Japan's ODA. Grant aid began in 1968 in the form of food aid, and in the 1990s, after temporarily achieving the status of the world's top donor, Japan has provided a cumulative total of approximately 5.46 trillion yen (JICA's portion, up to FY2023) to countries around the world to date.

Civil engineering projects for infrastructure development, such as roads, bridges, ports, and agricultural irrigation, account for the majority of grant aid. Except for the use of soil for construction work, the local soil is processed and used exclusively in the construction process. However, there are cases where special soils that are not commonly found in Japan are encountered at sites in various countries. In many cases, insufficient attention is not paid to them in construction planning. Therefore, it is difficult to foresee the impact during the preliminary design survey, and even if it is known, it is not always sufficient to evaluate the impact during and after construction and take appropriate countermeasures. As a result, we have often faced cases of major design changes and construction period extensions that increased the project cost at the time of construction.

In this basic research, we collected and organized examples of encounters with problem soils and countermeasures that have been taken in past ODA infrastructure development projects. Specifically, the handbook is intended as a reference material for practitioners to recognize and understand in advance the presence or absence of problem soils and their risks in the target countries at the survey and design stages, and to reduce the risks of facing problem soils as much as possible. In compiling the results, we held an expert opinion exchange meeting consisting of Japanese researchers and private consultants specializing in geotechnical engineering and improvement, slope disaster prevention, and agricultural civil engineering, who have been conducting research in collaboration with overseas research institutions. The chairperson of the committee, Professor Naoaki Suemasa of Tokyo City University, and each member of the committee provided valuable advice in consolidating the results of their work. We would like to take this opportunity to express our sincere appreciation to all parties involved for their cooperation.

In conclusion, we sincerely hope that this handbook will be of great use not only to ODA infrastructure projects but also to practitioners engaged in the design and construction of civil engineering projects overseas, and that it will be of great help when considering reinforcement measures for special soils and local natural geomaterials in developing countries. We would also appreciate constructive comments from the readers of this report, as this research is still in progress and continuous accumulation of knowledge is desirable.

May 2025

Naofumi Yamamura, Director General

Financial Cooperation Implementation Department

Japan International Cooperation Agency (JICA)

On the Occasion of Publication

Throughout the world, there are soils that are rarely encountered in Japan. While many of these soils are harmonious with humans, creating unique local landscapes and specialty products, some soils are very troublesome. Such soils are called “problem soils,” and they are especially difficult to handle and troublesome in construction work or in the maintenance of structures.

Due to the influence of the nature and origin of the parent material on these problem soils, the distribution of these soils is relatively limited. Furthermore, despite being classified as problematic soils with the same designation, slight variations in their composition may lead to substantial differences in their undesirable characteristics. Consequently, measures that have been effective in other areas may be rendered meaningless or excessive, even for the same problem soil.

As problem soils are often found in developing countries, the nature of these soils and countermeasures are not always communicated clearly, and post-event analysis is not always conducted thoroughly. Given these situations, problem soils persist, creating ongoing challenges.

This handbook was prepared in light of cases in which engineers, staff members, and related technicians directly involved in various JICA projects have encountered problem soils in the course of promoting grant aid projects mainly in developing countries, which have caused significant delays or inflated construction schedules and costs, or have caused unexpected obstacles to structures after construction, The purpose of this report is to provide a correct understanding of problem soils in order to reduce their risks and ensure the quality of structures. However, due to the “special nature” of problem soils, it is difficult and pointless to present the sole correct method of dealing with problem soils, and the purpose of this handbook is only to provide clues to solving problems when encountering problem soils. Due to time constraints, this handbook mainly covers expansive, dispersive, collapsible soils and laterite that are frequently encountered. In the course of the work, we collected as much information as possible on these problem soils, not only on paper but also by visiting various places around the world. For each problem soil, this handbook provides information on the reasons why it is classified as a problem soil, the areas where it is distributed, and the processes by which it is created, as well as a wealth of examples of damage, methods of judgment, and countermeasures. At the end of the book, test standards and judgment methods of each country are also described.

It is our sincere hope that this handbook will serve as an opportunity to accumulate information on problem soils so that they will eventually cease to be a nuisance. We would like to express our sincere gratitude to the members of the committee, JICA, and Nippon Koei.

May 2025

Prof. Naoaki Suemasa, Tokyo City University

Chairman of Project Research Expert Opinion Exhange Meeting

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CHAPTER 1. OVERVIEW OF THE HANDBOOK

1.1 PURPOSE OF THE HANDBOOK

There are numerous types of soils around the world that pose specific challenges for infrastructure development projects. These soils are collectively referred to as “problem soil”. Problem soil commonly encountered in geotechnical engineering include soils that undergo significant volume changes due to shrink-swell behavior, soils with inherently low strength, and soils that may induce chemical reactions such as corrosion of structures.

Encountering such soils during implementation of infrastructure development projects, especially in large-scale public works, poses substantial difficulty in formulating appropriate countermeasures. While the presence of problem soil can sometimes be identified during the planning, investigation, or design phases, in many cases they are often discovered during construction or even at the maintenance stage. This uncertainty creates significant risk, potentially necessitating revisions to the design, increased construction costs, and project delays.

The objective of this handbook is to provide a systematic knowledge base and practical insights into the identification, risk assessment, and mitigation strategies for handling problem soil. The handbook has been compiled based on a wide array of cases and countermeasure techniques observed in developing countries, particularly within the framework of JICA grant aid projects and yen loan-financed projects.

By proactively identifying the potential distribution of problem soil, understanding their associated risks, and preparing feasible countermeasures during all phases—from planning and investigation to design, construction, and maintenance—it is possible to minimize technical and financial risks and improve the overall quality of infrastructure projects.

It is essential to emphasize that this handbook is not intended to serve as a prescriptive guideline or engineering code. Instead, it is designed to serve as a reference resource for project proponents, design consultants, contractors, and engineers—offering guidance and technical insight when dealing with problem soil. The final judgment and application of countermeasures remain the responsibility of the executing agency, the project team, and the engineering professionals involved.

1.2 TARGET GROUP FOR THE HANDBOOK

This handbook is intended for a wide range of professionals involved in the planning, design, construction, and maintenance of infrastructure projects, particularly those funded by JICA through grant aid and yen loan programs. The primary users are outlined in Table 1.2.1.

Table 1.2.1 Target group for the Handbook

Target	Description
Reader	- Engineering consultants working on JICA grant aid and yen loan projects - Construction companies involved in JICA-funded projects - JICA staff (both headquarters and overseas offices) - Government counterpart engineers in developing countries Additional audiences may include: - Japanese engineers and consultants participating in infrastructure development in developing regions
Project Type	- Road development projects (including highways and local roads) in regions with problem soil conditions, funded by JICA grant aid or yen loans Additional applications may include: - Road construction projects implemented directly by the governments of developing countries - Non-road infrastructure projects such as irrigation systems, dams, and river embankments - Building construction projects where foundation soils present geotechnical challenges

Target	Description
Soil Type Covered	- Expansive (swelling) soils - Dispersive soils - Collapsible soils - Lateritic soils - Other types of problematic (special) soils Note: The handbook focuses primarily on expansive, dispersive, collapsible, and lateritic soils, which are common in developing countries. For other problem soils, only overview-level information is provided to raise awareness of potential risks.

Source: JICA Study Team

1.3 HANDBOOK PREPARATION POLICY

In preparing this handbook, the following points were considered:

i. To include as comprehensively as possible basic information on the types of problem soils, their issues, and countermeasures, thereby enabling the reader to understand the existence and risks of problem soils.

ii. When describing problem soils, to include a summary of the chapter at the beginning, allowing the reader to grasp the main points of the handbook without needing to read the details thoroughly.

iii. To omit detailed explanations of various countermeasure methods and instead organize only the key points of these methods to facilitate understanding.

Note: It is assumed that readers will refer to specialized books on each countermeasure method for detailed information.

Table 1.3.1 shows the structure and positioning of the handbook. The problem soil primarily addressed here are "expansive soils," "dispersive soils," "collapsible soils," and "laterite," which are widely distributed around the world and are often encountered in development projects. For these problem soils, past cases of encounters, responses at each stage of planning and design, and applicability of problem soil countermeasure technologies are summarized. For other problem soils, an overview is provided for the purpose of raising awareness. The handbook includes a method for determining expansive soils, which are particularly widespread among problem soils. This method is based on their soil properties. The handbook also includes a determination of expansive soil and dispersive soil based on chemical indicators. In addition, it contains standards for various tests. Furthermore, it includes Q&A sections and case studies for problem soil, list of symbols and abbreviations, and references as appendixes.

Table 1.3.1 Handbook structure and positioning

Chapter	Item	Content	Positioning
Chapter 1	Overview of the Handbook	- Purpose of the Handbook - Target Group for the Handbook - Handbook Preparation policy - Basic Information of Problem Soil - Basic Consideration Infrastructure Projects involving Problem soil	Explanation of the Handbook's Overview and Structure
Chapter 2	Problem Soil in Developing Countries and Considerations for Project Implementation	- Overview - Examples of problem soils encountered in past construction projects - Responses at the planning and investigation stage - Responses at the design and construction	Examples of problem soils encountered in construction work, response methods at each stage, and problem soil countermeasure technologies and applicability

Chapter	Item	Content	Positioning
	- Expansive soil - Dispersive soil - Collapsible soil - Laterite	stage - Problem soil countermeasure technology and applicability - Points to note for consultants and construction companies - Responses at the maintenance stage	
Chapter 3	Other Problem Soils		Overview of each problem soil except Chapter 2, mainly for the purpose of calling attention
Chapter 4	Problem Soil Measures	- Overview of problem soil measures	Introduction of the outline of measures for problem soil
Chapter 5	Basic Policy for Infrastructure Development Projects related to Problem Soils	- Procedure for infrastructure development projects with problem Soil risks - Risk communication between stakeholders - Survey approach for problem soil - Recording, documentation and reporting	Risk management methods for infrastructure development projects
Chapter 6	About Problem Soil	- Definition of problem soil - Soil formation Process - Classification of problem soil - Problem soil distribution area - Use of soil taxonomy - Engineering problems of problem soils	Basic information about problem soil
Chapter 7	Conclusion	Future challenges and prospects	Issues and prospects for the future development of problem soil countermeasure technology
Appendix		- Method of Identifying Expansive Soil Based on Soil Properties - Identification of Expansive Soil and Dispersive Soil Based on Chemical Indices - Testing Standards in Japan, the United States, and the United Kingdom - Problem Soil Q&A - Case Studies of Problem Soil - List of Symbols - List of Abbreviations - References	

Source: JICA Study Team

1.4 BASIC INFORMATION OF PROBLEM SOIL

To appropriately address the risks associated with problem soils, it is essential to understand their fundamental characteristics—including definitions, formative factors, genesis processes, classification, distribution, soil taxonomy, and relevant geotechnical issues. Table 1.4.1 summarizes this basic information. For further details, refer to Chapter 6.

Table 1.4.1 Basic information of problem soil

Item	Content
Definition	Soils that cannot be designed or constructed using conventional geotechnical engineering methods alone (Geotechnical Society of Japan). This handbook primarily addresses soil-related issues encountered in developing countries.
Formative Factors	Formed through complex interactions among parent material, topography, climate, biological activity, anthropogenic influences, and the passage of time.
Formation Process	- Weathering - Climatic Conditions: Humid conditions, humid tropical climates, dry tropical/subtropical climates, cold climates - Sedimentation: Volcanic deposits, fluvial and lacustrine processes
Classification	- Mechanical Properties: Expansive soils, dispersive soils, erodible soils, collapsible soils, crushable soils, soluble ground, soft ground - Chemical Properties: Saline/sodic soils, (acid) sulfate/sulfide soils, carbonate soils, acid soils - Other Types: Laterite, loess, volcanic soils, coral soils and coral aggregates, mica-rich sands, glacial deposits, weathered or soft rock, dry soils
Distribution Area	- Distribution and simplified risk maps are provided for expansive soils, dispersive soils, collapsible soils, and laterite. - Additional maps sourced from various documents are included in the appendix of the final report.
Soil Taxonomy	Correlation between the World Soil Classification Database (HWSD) and identified problematic soil types.
Engineering Issues	Key engineering considerations for appropriately addressing and resolving challenges posed by problem soils.

Source: JICA Study Team

1.5 BASIC CONSIDERATIONS FOR INFRASTRUCTURE PROJECTS INVOLVING PROBLEM SOIL

Infrastructure development projects undertaken in regions where problem soils are present require a distinct risk management approach. This is due to the limited systematic accumulation of technical data on such soils and the inherently higher degree of uncertainty these projects entail compared to conventional undertakings. From a risk management perspective, it is essential to approach such projects with due attention to the key considerations outlined in Table 1.5.1. For further detail, refer to Chapter 5.

Table 1.5.1 Key considerations in Infrastructure development projects

Item	Content
Infrastructure Projects Involving Problem Soil Risks	Outlines the procedural flow for executing projects under problematic soil conditions, including the development of appropriate implementation frameworks and approaches to risk management.
Risk Communication Among Stakeholders	Emphasizes the importance of risk communication throughout all stages of the project and provides guidance on communication strategies and stakeholder coordination.
Survey Planning for Problem soil	Describes key considerations in planning and conducting geotechnical investigations for infrastructure development on problem soils.
Documentation and Reporting	Highlights the significance of systematic record-keeping and information sharing, including data transfer protocols, to ensure continuity and quality assurance throughout the project lifecycle.

Source: JICA Study Team

CHAPTER 2. PROBLEM SOIL IN DEVELOPING COUNTRIES AND CONSIDERATIONS FOR PROJECT IMPLEMENTATION

This section provides a comprehensive overview of problem soils commonly encountered in developing countries, including typical case studies, applicable countermeasures, and critical considerations across each stage of project implementation. The soils addressed—namely expansive soils, dispersive soils, collapsible soils, and lateritic soils—are widely distributed in tropical and subtropical regions and are frequently associated with geotechnical failures and performance deficiencies in civil engineering projects.

For a detailed understanding of the underlying mechanisms, identification methods, and engineering solutions for these soils, reference should be made to the report titled:
"Basic Study on Reinforcement Measures for Local Natural Geomaterials and Problematic Soil Measures Encountered in Construction Works in Developing Countries".

The categories of problem soils discussed in this chapter are as follows. Additional types of problem soils are addressed in Chapter 3.

Mechanical property	Expansive soil, dispersive soil, collapsible soil (mainly for loess)
Chemical Properties	N/A
Other	Laterite

2.1 EXPANSIVE SOIL

2.1.1 Summary

Expansive soils are among the most critical types of problem soils in geotechnical engineering, defined by their pronounced swelling upon wetting and shrinkage upon drying. These volume changes, driven by seasonal moisture variations, can result in severe structural damage due to surface cracking, differential heave, and settlement. While similar behavior occurs in typical cohesive soils, expansive soils exhibit far greater magnitude of deformation.

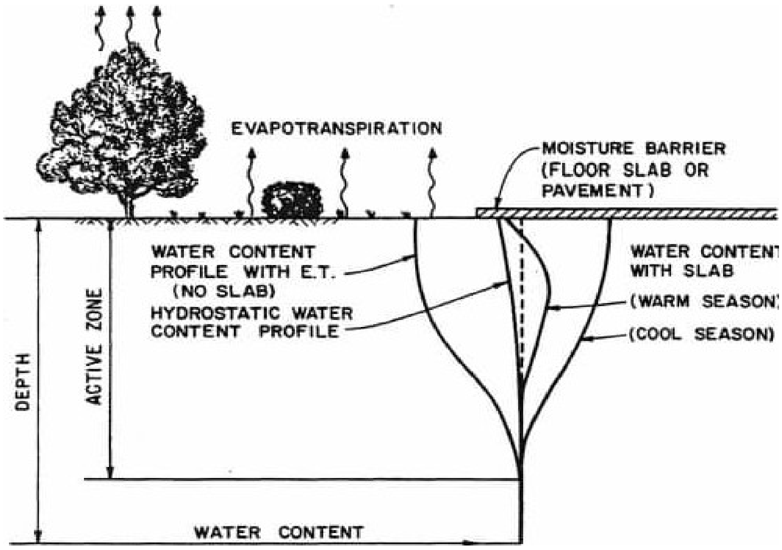
This behavior is primarily due to the presence of water-absorbing clay minerals—particularly smectite. The higher the content of such minerals, the greater the swelling potential and water uptake. These cyclic volume changes pose significant challenges for foundations, pavements, and other infrastructure.

Despite their prevalence—especially in arid, semi-arid, and tropical regions—expansive soils display considerable variability across locations. Furthermore, few countries have established detailed engineering standards specifically for addressing their effects.

To ensure effective mitigation, it is essential to have a comprehensive understanding of the soil's physicochemical behavior. This understanding shall be supported by thorough site investigations, rational design, and sound construction practices. A multidisciplinary approach integrating geotechnical assessment, material characterization, and contextual engineering judgment is essential for reliable design and long-term performance.

2.1.1.1 Depth at which expansive soils become problematic

Expansive soils may exist to depths of up to 20 meters; however, problematic behavior is generally limited to the depth range where moisture content fluctuates due to seasonal wetting and drying. This depth range, referred to as the active zone, generally extends up to approximately 3 meters when the groundwater table is sufficiently deep. The active zone may reach greater depths under certain climatic conditions. A shallow groundwater table results in a correspondingly shallower active zone. In instances where expansive soils are present below the groundwater table and moisture variation is minimal, swelling behavior does not occur.



Source: EXPANSIVE SOILS Problems and Practice in Foundation and Pavement Engineering, John D. Nelson, Debora J. Mille, JOHN WILEY & SONS, INC.(1992).

Figure 2.1.1 Range of variation in moisture content (Active zone)

2.1.1.2 Factors affecting swelling and shrinkage

The swelling behavior of expansive soils is governed by a complex mechanism influenced by multiple interrelated factors. Swelling occurs as a result of moisture-induced disturbances in the internal stress equilibrium of the soil matrix. Many factors that contribute to swelling are either governed by or exert influence upon intrinsic soil properties such as plasticity, density, and mineral composition.

Table 2.1.1 and Table 2.1.2 summarize the key soil properties and environmental conditions that affect swelling and shrinkage behavior.

Table 2.1.1 Soil Properties Affecting Swelling and Shrinkage

Factor	Description
Clay mineralogy	Clay minerals which typically cause soil volume changes are montmorillonites, vermiculites, and some mixed layer minerals. Illites and kaolinites are rarely expansive, but they can cause volume changes when particle sizes are extremely fine (less than a few tenths of a micron)
Soil water chemistry	Swelling is repressed by elevated cation concentration and augmented cation valence. For instance, the presence of Mg^{2+} cations in soil water would result in a lower degree of swelling than would Na^{+} cations
Soil suction	Soil suction is a stress variable that is effective in isolation. It is represented by the negative pore pressure in unsaturated soils. Soil suction is influenced by saturation, gravity, pore size and shape, surface tension, and the electrical and chemical characteristics of the soil particles and water
Plasticity	In general, soils that demonstrate plastic behavior over a wide range of moisture content and that possess high liquid limits exhibit greater potential for both swelling and shrinking. Plasticity is an indicator of swell potential
Soil structure and fabric	It has been demonstrated that flocculated clays generally exhibit greater expansive tendencies compared to dispersed clays. The presence of cemented particles impede the process of swelling. Fabric and structure are altered by compaction at higher water content or remolding. Kneading compaction has been shown to yield dispersed structures with reduced swell potential compared to soils that are statically compacted at reduced water contents
Dry density	Higher densities generally indicate smaller particle spacing, which may result in increased repulsive forces between particles and larger swelling potential

Source: EXPANSIVE SOILS Problems and Practice in Foundation and Pavement Engineering, John D. Nelson, Debora J. Mille, JOHN WILEY & SONS, INC.(1992).

Table 2.1.2 Environmental Conditions Affecting Swelling and Shrinkage

Factor		Description
Initial Moisture Conditions		A desiccated expansive soil exhibit a higher affinity for water, or higher suction, in comparison to the same soil at higher water content, lower suction. Conversely, a wet soil profile will lose water more readily when exposed to drying influences and will shrink more than a relatively dry initial profile. The initial soil suction must be considered in conjunction with the expected range of final suction conditions
Moisture variations	Moisture	Changes in moisture content in the active zone near the upper part of the profile primarily define heave. It is in those layers that the widest variation in moisture and volume change will occur.
	Climate	The amount and variation of precipitation and evapotranspiration greatly influence the moisture availability and depth of seasonal moisture fluctuation. Seasonal heave is at its greatest in semiarid climates with pronounced, short wet periods
	Groundwater	Shallow water tables provide a source of moisture
	Drainage and manmade water sources	Surface drainage features, such as ponding around a poorly graded house foundation, provide sources of water at the surface. Leaky plumbing on the other hand, can allow the soil access to water at greater depths
	Vegetation	Trees, shrubs, and grasses deplete moisture from the soil through transpiration. This process causes the soil to be differentially wet in areas of varying vegetation
	Permeability	Soils with higher permeabilities, particularly due to fissures and cracks in the field soil mass, allow faster water migration and promote faster rates of swelling
	Temperature	As temperature rise, moisture is drawn to cooler areas beneath pavements and buildings
Stress Conditions	Stress history	An over-consolidated soil is more expansive than the same soil at the same void ratio and normally consolidated. Swell pressures can increase with the aging of compacted clays. However, the amount of swell under light loading has been shown to be unaffected by aging. Repeated wetting and drying tend to reduce swell in laboratory samples, but after a certain number of wetting-drying cycles, swell is unaffected
	In-situ conditions	The initial stress state in a soil must be estimated in order to evaluate the probable consequences of loading the soil mass and/or altering the moisture environment therein. The initial effective stresses can be estimated through sampling and testing in a laboratory, or in-situ measurements and observations
	Loading	The magnitude of surcharge load determines the amount of volume change that will occur for a given moisture content and density. An externally applied load acts to balance interparticle repulsive forces and reduce swelling
	Soil profile	The thickness and location of potentially expansive layers in the profile considerably influence potential movement. The greatest movement is expected to occur in profiles with expansive clays extending from the surface to depths below the active zone. Movement will be reduced if expansive soil is overlain by non-expansive material or overlies bedrock at a shallow depth

***Source**: Expansive Soils: Problems and Practice in Foundation and Pavement Engineering, John D. Nelson & Debora J. Miller, John Wiley & Sons, Inc. (1992) - The format has been changed by the JICA study team.*

2.1.1.3 Origin of Expansive Soils, Parent Materials, and Clay Minerals

The development of expansive soils is attributed to a diverse array of parent materials, including alluvial, colluvial, and lacustrine sediments, marls, calcareous rocks, and basic igneous, metamorphic, and volcanic formations. While their geologic origins differ, these materials are typically rich in feldspar and ferromagnesian minerals. The weathering of such rocks under basic environmental conditions leads to the formation of residual clays with expansive characteristics.

In cases where the parent material is not inherently basic, alkaline earth elements may be introduced through processes such as groundwater seepage or episodic flooding, enhancing the soil's swelling potential.

A typical example is the tropical *black cotton soil* (BCS) found in East Africa and India, which is primarily derived from the weathering of basaltic rock. However, even soils classified as expansive may exhibit significant regional variation in their properties due to differences in parent material, weathering intensity, and pedogenic processes.

Table 2.1.3 to Table 2.1.6 summarize the parent materials and geologic origins of expansive soils in various regions around the world.

Table 2.1.3 Base Materials and Origins of Black Cotton Soils (BCS) in Africa

Region	Area / Country	Base Material / Origin
West Africa	Ghana, Togo, Benin	Precambrian metamorphic rocks (schist and gneiss)
	Côte d'Ivoire, upstream of the Volta River	Eutrophic brown soils (generally non-problematic)
	Cape Verde Peninsula, Senegal	Limited black clay occurrence; residual soils over small basic intrusions
	Nigeria	Residual and alluvial soils; pre-Tertiary volcanic rocks (Biu and Meringa); scattered remnants of basalt flows; black alluvium in the Benue River basin; lake and alluvial deposits in the Chad Basin; calcareous rocks along Bauchii–Gombe–Yola road
East Africa	Ethiopia	Rift valley topography; volcanic rocks
	Kenya	Basic volcanic rocks in tropical regions
	Malawi, Zambia	Rift valley topography
	Tanzania	Rift valley setting with basic volcanic rocks
	Uganda	Basic volcanic-derived soils; lowland regions around rift valley lakes
	Sudan	Volcanic terrain along the rift; lacustrine and alluvial soils of the White and Blue Nile floodplains
	Somalia	Highland basalt
Central Africa	NE Nigeria, N Cameroon, S Chad	Lacustrine and alluvial soils in the Chad Basin
	N Cameroon, NE Nigeria	Basic intrusive rocks
	Congo Rift Valley region	— (data not specified)
	Angola (South)	Basic rocks
	Luanda	Calcareous rocks
Southern Africa	South Africa, Zimbabwe (formerly Rhodesia)	Derived from basic intrusive and extrusive rocks: norite, basalt, dolerite
	Botswana	Alluvial deposits, swamp deposits, and basic rocks
	Lesotho, Eswatini (formerly Swaziland)	Basalt
	Zimbabwe	Karoo volcanic rocks
	Malawi (specific subregion unclear)	Basalt and alluvial deposits
North Africa	Morocco	Derived from shale and fine-grained sedimentary rocks; alluvial soils

Source: JICA Study Team

Table 2.1.4 Base Materials and Origins of Expansive Soils in Asia

Country	Region	Base Material / Origin
India	Deccan Plateau	Deccan Trap basalt and gneiss
	Gujarat	—
	Western Rajasthan	—
Indonesia	Central and Eastern Java	Claystone, clay shale, shale, volcanic ash
	Sulawesi	Derived from ancient volcanic activity
China	Sichuan Basin	Mudstone and shale
	Southern China	Formed through tropical and subtropical weathering; volcanic ash and volcanic rocks (especially andesite and basalt)
	Yellow River Basin	Loess deposits of the Loess Plateau
	Xinjiang Uygur Autonomous Region	Sedimentary rocks in arid environments; salt lake sediments
Pakistan	Indus River Basin and Punjab Region	Alluvial sediments and volcanic-derived materials
Oman	Foothills of the Oman Mountains, area around Duqm	Bentonite-bearing mudstone, marl, silty mudstone, clayey dolomitic limestone, altered conglomerate
Iran, Iraq, Turkey	Central Highlands, Caspian Sea coast	Sediments derived from salt lakes and arid regions
Australia	—	Basalt

Source: JICA Study Team

Table 2.1.5 Base Materials and Origins of Expansive Soils in the Americas

Country	Region	Base Material / Origin
United States	Texas, Oklahoma, Colorado, California, Utah, Arizona, Missouri, Kansas	Volcanic ash deposits; clay-rich shale formations
Canada	Alberta, Saskatchewan, Manitoba	Fluvial and glacial deposits; clay shale
Mexico	Central Mexican Plateau, Baja California, Northern Arid Regions	Volcanic sediments; deposits from arid environments
Brazil	Central Plateau (Cerrado), Minas Gerais	Weathered mountain rocks and sedimentary formations
Argentina	Pampas Region, Patagonia	Fluvial sediments and arid zone deposits
Bolivia	Altiplano Plateau	Lacustrine (salt lake) sediments and clay minerals formed in arid regions
Colombia	Andean Valleys and Tropical Humid Zones	Volcanic ash-derived soils

Source: JICA Study Team

Table 2.1.6 Base Materials and Origins of Expansive Soils in Europe

Country	Region / Area	Base Material / Origin
France, Italy, Spain, England, Germany, Hungary, Poland, Romania	—	Volcanic ash, sedimentary rocks (particularly mudstone), fluvial sediments, salt lake deposits
Sweden	—	Glacial deposits

Source: JICA Study Team

2.1.1.4 Formation Processes of Expansive Soils

The formation of expansive soils, particularly those classified as Vertisols, involves a series of distinctive pedogenic processes. The most commonly recognized mechanisms include:

i. Cracking and swelling
ii. Self-mulching
iii. Soil churning
iv. Development of slickensides, sphenoids, and bowl-shaped microstructures
v. Formation of kankar (calcareous nodules)
vi. Dark surface coloration
vii. Smectite clay mineral formation
viii. Clay translocation

These processes contribute to the distinctive physical and mineralogical characteristics of Vertisols. A summary of typical soil formation processes in Vertisols is presented in Table 2.1.7.

While several conceptual models have been proposed to explain Vertisol genesis, the soil mechanics-based model illustrated in Figure 2.1.2 offers a comprehensive understanding of the development mechanisms of expansive soils from a geotechnical perspective.

Table 2.1.7 General Soil Formation Processes in Expansive Soils (Vertisols)

Soil Formation Process	Description
Cracking and Expansion	Repeated wetting and drying cycles result in the development of deep, wide, polygonal cracks.
Self-Mulching	Progressive disintegration of the surface layer into fine aggregates and crumbs due to repeated shrink-swell cycles.
Soil Churning (Agitation)	Mechanical mixing of soil materials in the upper horizon, typically occurring in conjunction with self-mulching.
Formation of Slickensides, Sphenoids, and Bowl Structures	Smooth shear planes (slickensides, sphenoidal features) form within cracks during the wetting phase when the soil is in a plastic state.
Kankar Formation	Development of calcium carbonate nodules (*kankar*) commonly observed in Vertisols.
Darkening	Occurs in topographic depressions or seasonally waterlogged areas due to the accumulation of organic matter.
Smectite Formation	Smectite clay minerals form under alkaline conditions with sufficient availability of Ca^{2+} and Mg^{2+} in the soil profile.
Clay Translocation	Fine smectitic clays with high specific surface area become dispersed, mobilized, and subsequently accumulate in subsurface horizons.

Source: JICA Study Team

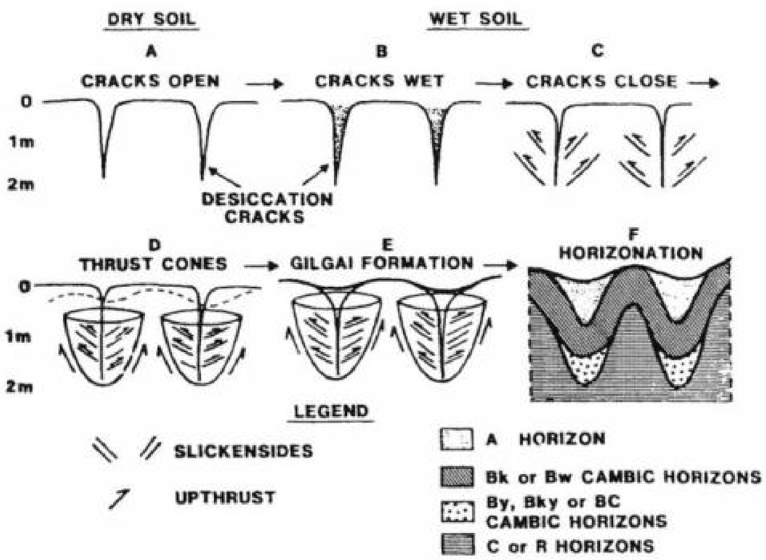


Fig. 2.6. Schematic illustration of possible stages (A–F) in the formation of slickensides, gilgai and cyclic horizonation (Wilding and Tessier, 1988).

Source: VERTISOLS AND TECHNOLOGIES FOR THEIR MANAGEMENT, N. AHMAD, A.MERMUT, ELSEVIER, 1996

Figure 2.1.2 Soil mechanics model (Wilding & Tessier, 1988)

2.1.2 Examples of Problem Soils Encountered in Past Construction Project

Expansive soils have been associated with a wide range of geotechnical and structural failures in civil engineering projects. Typical manifestations include:

- Deformation and cracking of residential and commercial buildings
- Road surface heaving and pavement distress
- Embankment deformation and localized slope failures
- Surface rupture and slip failures in cut slopes
- Channel bank instability and revetment damage
- Structural damage or collapse of retaining walls and underground structures
- Lining and pavement failures in tunnels

These issues may appear shortly after construction—sometimes within months—or may emerge gradually over a period of 3 to 5 years. Problems often arise when external events alter the soil moisture regime, such as changes in drainage, irrigation, or extreme weather events. However, damage often manifests after a time lag following construction completion.

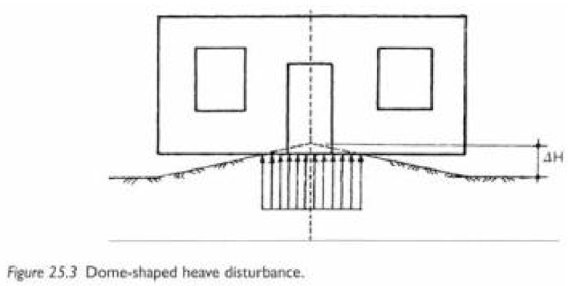
Given that the severity of damage can range from minor maintenance issues to substantial structural failures, projects located in areas with known expansive soil distributions require careful consideration at every stage: investigation, design, construction, and maintenance. This section provides representative case histories to support the identification and understanding of such risks in the target regions. These examples serve as a basis for determining the appropriate engineering response and risk mitigation strategies.

[Explanation.]

2.1.2.1 Examples of Buildings and Houses

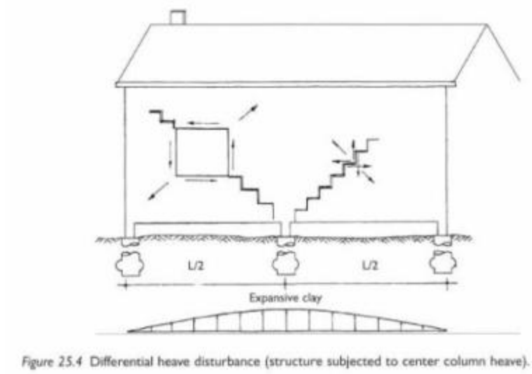
Structures constructed on lightly loaded slabs or shallow foundations—such as residential houses, motels, and garages—frequently exhibit damage attributable to expansive soil behavior. Typical symptoms include irregular cracking patterns, downward movement of corners (corner drop), uplift-induced ridging near the center of walls, minor rotation of stem walls, outward horizontal displacement, and slight rotational distortion of building corners around a vertical axis (Popa, 1997).

The predominant mode of structural movement in such cases is upward or domed heave, with the maximum vertical displacement often occurring at or near the center of the building footprint. This domed uplift produces tensile stresses along the edges and corners, leading to characteristic cracking patterns consistent with corner-down deformation.



Source: Expansive Soils Recent advances in characterization and treatment, Amer Ali Al-Rawas, Mattheus F.A. Goosen(2006)

Figure 2.1.3 Dome-shaped uplifted deformation



Source: Expansive Soils Recent advances in characterization and treatment, Amer Ali Al-Rawas, Mattheus F.A. Goosen(2006)

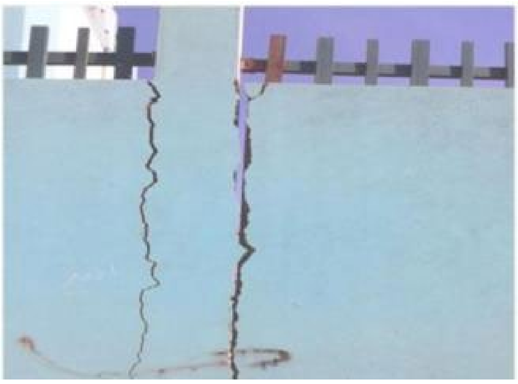
Figure 2.1.4 Pattern of damage to homes due to dome uplift.

Source: Expansive Soils Recent advances in characterization and treatment, Amer Ali Al-Rawas, Mattheus F.A. Goosen, Taylor & Francis (2006).

Figure 2.1.5 Example of damage to a house (wall cracks)

Source: https://www.hie-ce.com/blog/is-your-home-built-on-expansive-soil

Figure 2.1.6 Example of damage to a house (cracks in the foundation)



Source: Damages of Buildings on Expansive Soils: Diagnosis and Avoidance, Magdi M. E. Zumrawi, Asim O. Abdelmarouf, and Abubakr E. A. Gameil (2017).

Figure 2.1.7 Example of damage to a house (wall cracks)

Source: Damages of Buildings on Expansive Soils: Diagnosis and Avoidance, Magdi M. E. Zumrawi, Asim O. Abdelmarouf, and Abubakr E. A. Gameil (2017)

Figure 2.1.8 Example of damage to a house (wall cracks)

Source: Damages of Buildings on Expansive Soils: Diagnosis and Avoidance, Magdi M. E. Zumrawi, Asim O. Abdelmarouf, and Abubakr E. A. Gameil (2017).

Figure 2.1.9 Example of damage to a house (foundation)

Source: Damages of Buildings on Expansive Soils: Diagnosis and Avoidance, Magdi M. E. Zumrawi, Asim O. Abdelmarouf, and Abubakr E. A. Gameil (2017).

Figure 2.1.10 Example of damage to a house (floor)

2.1.2.2 Examples of Roads

The construction of roads over water-sensitive expansive soils often poses significant geotechnical challenges. Pavement movements in such conditions typically resemble those observed in lightly loaded structures, with comparable patterns of distortion. The nature and extent of deformation vary depending on factors such as the thickness of the expansive soil layer, proximity of vegetation (e.g., trees), and spatial variations in moisture content.

In severe cases, extensive heave and collapse of the entire pavement section may occur. Figure 2.1.11 schematically illustrates the deformation mechanism of roadways affected by expansive soils.

Initially, precipitation or artificial water application in the vicinity of the roadway leads to moisture infiltration and swelling of the surrounding subgrade, causing uplift of the pavement. Over time, moisture migrates toward the center of the road, leading to progressive uplift. During the dry season, the outer edges of the roadway begin to dry and contract, while the center retains moisture, resulting in a characteristic domed profile. Because water drainage from the central portion is limited, shrinkage does not occur uniformly, and subsequent wet seasons induce further swelling, compounding the uplift behavior over time.

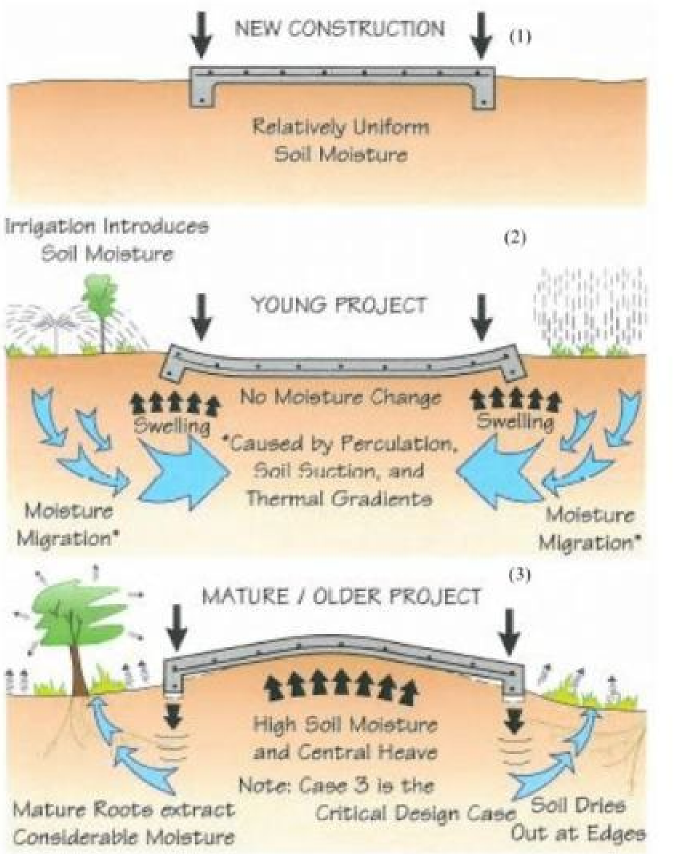


Figure 2.5 Damage progression under expansive soil. (1) New foundation construction above expansive soil, which often has relatively uniform soil moisture. (2) Water from irrigation and rainfall moves under the perimeter of the foundation, resulting in edge lift. (3) Many years after construction, the water will eventually transfer under the centre of the foundation, resulting in centre lift (Day 2010).

Source : Adverse Effects of Expansive Soils on Road Infrastructure and Evaluation of Chemical Remediation Techniques, Hayder Abbas Hasan (2019).

Figure 2.1.11 Progression of road deformation

Source: Enhancing the Engineering Properties of Subgrade Materials Using Processed Waste: A Review, .I Y. Amakye, S. J. Abbey, C. A. Booth and D. Mahamadu (Oct . 2021)

Figure 2.1.12 Examples of Road Damage (Swell)

Source: https://mintekresources.com/expansive-soils/

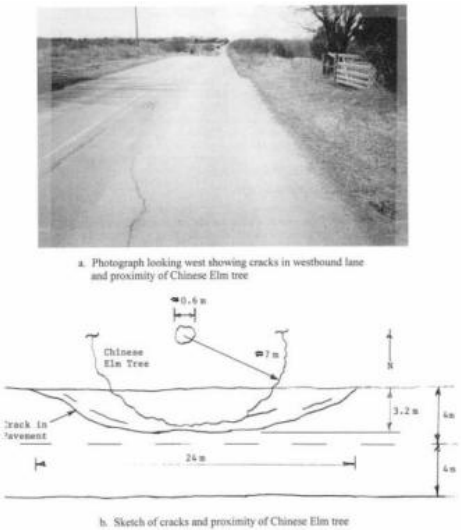
Figure 2.1.13 Examples of Road Damage (Cracks)

Source: Evaluation of Damage to a Road and Sports Complex on Expansive Clays, M. B. Mgangira, P. Paige-Green (2008).

Figure 2.1.14 Cross Section of Road Crack

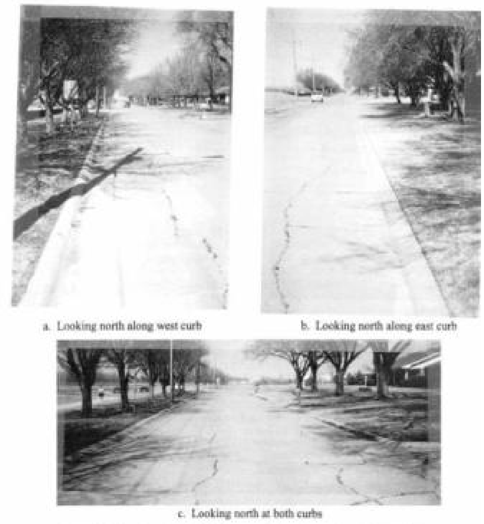
Source: Evaluation of Damage to a Road and Sports Complex on Expansive Clays, M. B. Mgangira, P. Paige-Green (2008).

Figure 2.1.15 Propagation of Cracks in Depth Direction



Source: EXPANSIVE CLAY SOILS AND VEGETATIVE INFLUENCE ON SHALLOW FOUNDATIONS, C. Vipulanandan, Marshall B. Addison, Michael Hasen(2001)

Figure 2.1.16 Cracks in road caused by tree roots



Source: EXPANSIVE CLAY SOILS AND VEGETATIVE INFLUENCE ON SHALLOW FOUNDATIONS, C. Vipulanandan, Marshall B. Addison, Michael Hasen(2001)

Figure 2.1.17 Cracks in road caused by tree roots

Figure 2.1.18 Muddy unpaved road

2.1.2.3 Examples of Embankments

A case of slope failure occurred in an industrial park in Indonesia due to slaking of clay shale after slope excavation (see Figure 2.1.19). Although the embankment was temporarily covered with blue sheeting during the rainy season, a near-complete slope ended up failing during periods of intense rainfall.

When expansive soils are used as fill, their swell potential can increase by a factor of 5 to 10 compared to their natural in-situ condition. Therefore, extreme caution is required when employing such materials in embankment construction.

Source: JICA Study Team

Figure 2.1.19 Damage to Embankment Slope (Indonesia)

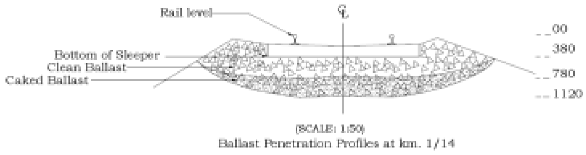
Source: Understanding the performance of expansive subgrade materials treated with non-traditional stabilizers: A review, Samuel Y. Amakye, Samuel J. Abbey(2021)

Figure 2.1.20 Slip Failure of Road Embankment Slope

Figure 2.1.21 illustrates track deformation associated with swelling of expansive soils located beneath and possibly within a railway embankment. As deformation increases, track geometry is maintained through the repeated addition of ballast. Over time, the inserted ballast becomes intermixed with the underlying expansive soil, reducing the overall swell potential in the mixed zone. However, the ballast also facilitates moisture retention, which weakens the soil structure. Eventually, the continued deformation and strength degradation necessitate full-scale replacement of the affected embankment sections.

Source: JICA Study Team

Figure 2.1.21 Deformation of railroad track due to expansive soil (India)



Source: Consultancy Report On Rehabilitation Of Weak Formation Between Miraj and Kolhapur Stations, Pune Division : Central Railway, 2007

Figure 2.1.22 Ballast Penetration in Indian Railways

2.1.2.4 Examples of Slopes

In cut slopes, changes in atmospheric pressure often induce localized rises in groundwater levels. When expansive soils are present within such slopes, these materials—initially dry and mechanically stable—may absorb infiltrating water, swell, and subsequently lose shear strength, leading to slip failures. Groundwater level fluctuations caused by road construction activities or extreme rainfall events not previously experienced in the region can exacerbate this process. Rising groundwater within the slope body may create zones of reduced strength in expansive soils, triggering translational or rotational failures.

Cut slopes in areas where expansive soils are present must therefore be treated with particular caution, as they are prone to unexpectedly large-scale landslides, often necessitating substantial mitigation measures.

In Indonesia, clay shale is widely distributed. Upon cutting, slaking-weathering commences within a few days. Even if the pre-cutting N-value exceeds 60, adhesive strength can deteriorate rapidly from 80–90 kPa to near zero, and the internal friction angle may decrease drastically from 41° to as low as 9°. Repeated wetting and drying cycles progressively convert clay shale into an expansive soil, significantly compromising slope stability.

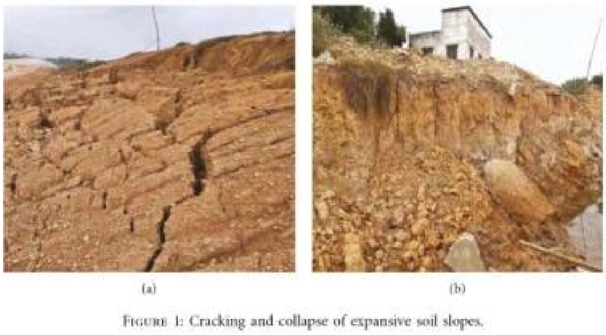
Figure 2.1.27 illustrates various types of slip failures observed in cut slopes composed of expansive soils. Notably, slip surfaces may retrogress upslope in a progressive manner. Accordingly, surface water infiltration control must be addressed comprehensively, often requiring slope-wide coverage and drainage systems.

Source: REMOTE SENSING AND GEOTECHNICAL INVESTIGATIONS OF EXPANSIVE SOILS, Fekerte Arega Yitagesu(2012)

Figure 2.1.23 Failure of a cut slope

Source: Mitigation of Expansive Soils Damages, Joseph Muhirwa, Richard Benda, Robert Sargent

Figure 2.1.24 Slope Failure

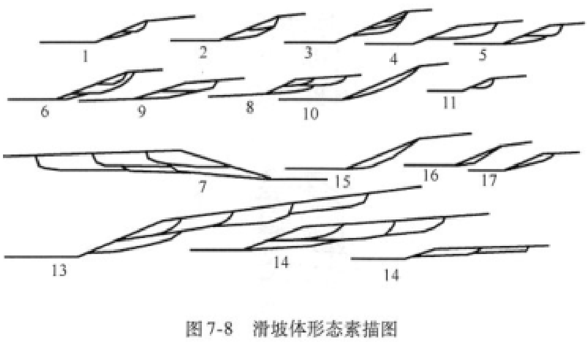


Source: Expansive Soil Embankment Filling and Cutting Treatment Technology: A Systematic Review, Zhen Huang, Hang Shi, Wei Zhang, Shaokun Ma, Feng Gao, Min Ma(2022)

Figure 2.1.25 Slope Failure

Source: Shear Strength and Durability Behaviors of Compacted Weathered Clay Shale Mixture Using Portland Cement, Pintor Tua Simatupang, Idrus M. Alatas Ayu K. Redyananda, Eko A. Purnomo(2022).

Figure 2.1.26 Clay shale cut slope collapse



Source: Expansive Soil Engineering for Roads, Zheng Jianlong and Yang Heping, People's Transportation Publishing House, 2009

Figure 2.1.27 Slope Failure Pattern of Expansive soil

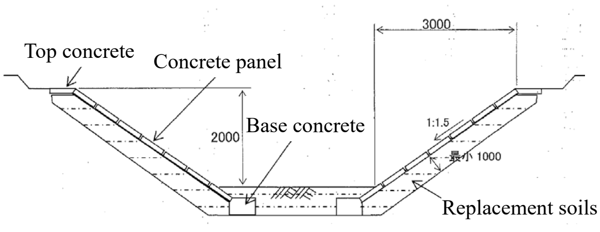
2.1.2.5 Case Study: Irrigation Canals and Water Conveyance Structures

In regions where expansive soils are present along irrigation canals or canal embankments, several types of deformation-related issues may arise. Typical problems include drying shrinkage cracks, irregular surface ridges on side slopes, and slope instability due to reductions in subgrade cohesion caused by moisture fluctuations. Such conditions can lead to localized or progressive slip failures.

A representative case was observed in Cambodia, where dispersive soils were identified in the project area, and expansive soil was used as replacement backfill behind concrete lining panels of an irrigation canal. Although laboratory tests (e.g., crumb tests) confirmed that the replacement material was non-dispersive, bulging of the slope occurred, leading to damage of the concrete lining. No prior failures had been reported in the area due to expansive soils, and thus the potential risk posed by expansive behavior was not considered in the design. This oversight contributed directly to the observed damage.

Source: JICA Study Team

Figure 2.1.28 Damage to Irrigation Canals (Cambodia)



Source: JICA Study Team

Figure 2.1.29 Design Cross Section of Waterway

It is imperative to acknowledge that expansive and dispersive soils may have common origins, stemming from similar parent materials and exhibiting comparable mineralogical compositions. Consequently, the presence of one may serve as an indication of the potential occurrence of the other. This underscores the necessity for thorough soil characterization and risk assessment during the planning and design of canal systems in such geologic settings.

2.1.2.6 Examples of Retaining Walls and Buried Structures

Buried structures such as retaining walls, culverts, and underground shelters are subject to expansive soil pressures acting in both horizontal and vertical directions. In particular, horizontal swelling pressures can become significant and may exceed the design capacity of rigid structural elements, leading to lateral displacement, tilting, or cracking.

Figure 2.1.30 (a) and (b) present damage observed in drainage channels within an industrial park. These drainage channels, constructed with thin reinforced concrete walls and designed only to resist standard earth pressure, were excavated and installed prior to backfilling. The backfill, composed of expansive soil, exerted unanticipated swelling pressures upon wetting, exceeding the load resistance of the structure and resulting in concrete failure. In some locations, entire sections of the channel collapsed due to the combined effects of swelling pressure and embankment-induced slippage from adjacent housing developments.

(a) Damage to drainage facilities (Indonesia)

(b) Damage to drainage facilities (Indonesia)

(c) Deformation due to swelling pressure on the culvert sidewall of road embankment (India) - Dry season

(d) Same, rainy season

Source: JICA Study Team

Figure 2.1.30 Example of deformation of retaining walls and buried structures due to expansive soil

Additional damage was documented in Figure 2.1.30 (c) and (d), which show a box culvert crossing a railway embankment in India. Lateral deformation of the culvert sidewalls was attributed to swelling pressure from adjacent expansive soil. The deformation intensified during the rainy season and did not fully recover during subsequent dry periods, indicating a progressive and cyclic deterioration pattern likely to recur annually.

These cases emphasize the critical importance of evaluating swelling pressures in the design of buried and embedded structures, particularly in regions where expansive soils are used as backfill or are present in natural ground conditions.

2.1.3 Actions to Be Taken at the Preliminary Survey Stage

At the planning and investigation stage, it is essential to appropriately assess whether expansive soils are present at the proposed project site and to determine the necessity of incorporating countermeasures into the project design. Expansive soils are commonly distributed in arid and semi-arid regions characterized by distinct wet and dry seasons.

To verify their distribution, reference should be made to the expansive soil distribution maps and geotechnical risk maps provided in this handbook. These tools allow for a preliminary assessment of the likelihood of encountering swell-prone soils. Subsequently, site-specific investigations and testing must be carried out to confirm the presence and extent of expansion in the soils associated with the project.

The most reliable method for identifying expansive soils is through mechanical testing to determine swelling strain and swelling pressure. However, conducting such tests across all sampled locations may not be feasible due to time and budget constraints. Therefore, an appropriate approach must be adopted at each project phase:

- Reconnaissance/Initial Site Investigation Stage: Utilize simple field identification techniques and empirical indicators.
- Preliminary Investigation Stage: Employ laboratory-based physical property tests (e.g., Atterberg limits, particle size distribution) to infer swell potential.
- Detailed Investigation Stage: Apply direct mechanical testing (e.g., oedometer swelling tests) to soils suspected of expansive behavior for design-level validation.

This staged methodology ensures efficient allocation of resources while maintaining a sufficient level of reliability in identifying and managing expansive soil risks.

[Explanation.]

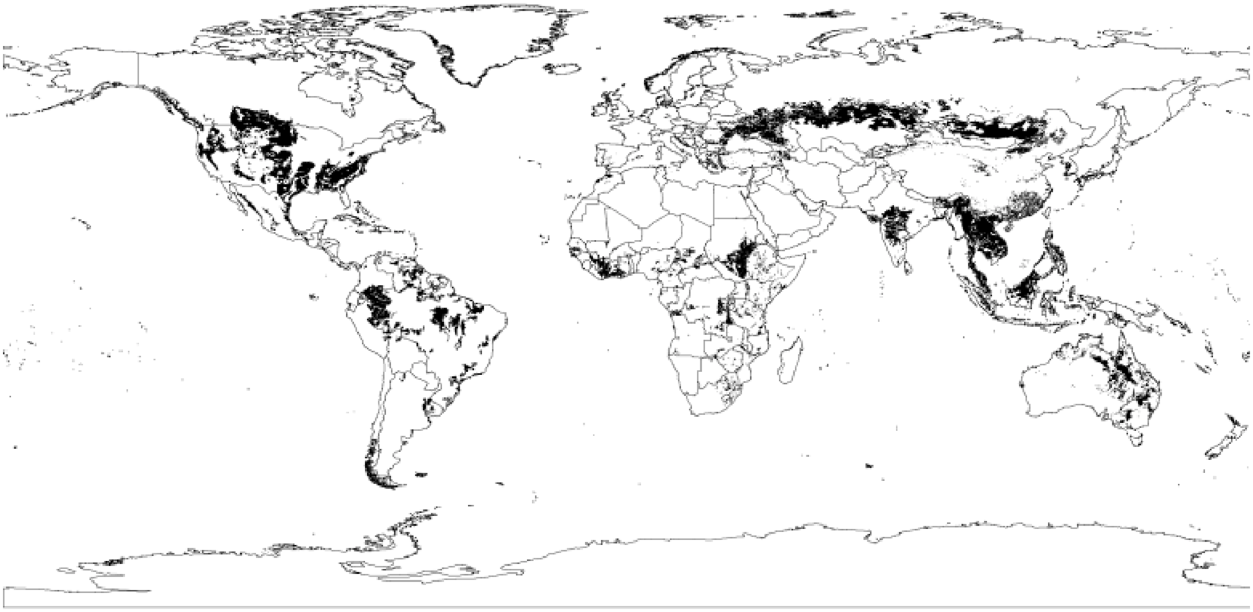
2.1.3.1 Estimated Problem Soil Distribution Map

Expansive soils are distributed across a wide range of geographic regions. Countries and areas known for expansive soil occurrences include:

- United States: Texas, California
- Asia: Thailand, Cambodia, Indonesia
- India: Deccan Plateau (Black Cotton Soils)
- Australia: Various interior regions
- Africa: Central and northern Nigeria, Nile River Basin in Sudan
- South America: Orinoco River Basin in Venezuela
- China: Sichuan Basin, parts of the Loess Plateau
- Europe: Southern France

An estimated distribution map of expansive soils, compiled from relevant national and international soil databases as well as published literature, is shown in Figure 2.1.31.

This map serves as a reference tool for identifying areas where expansive soil-related geotechnical issues are likely to arise and highlights regions requiring more detailed ground investigation and specialized design considerations.

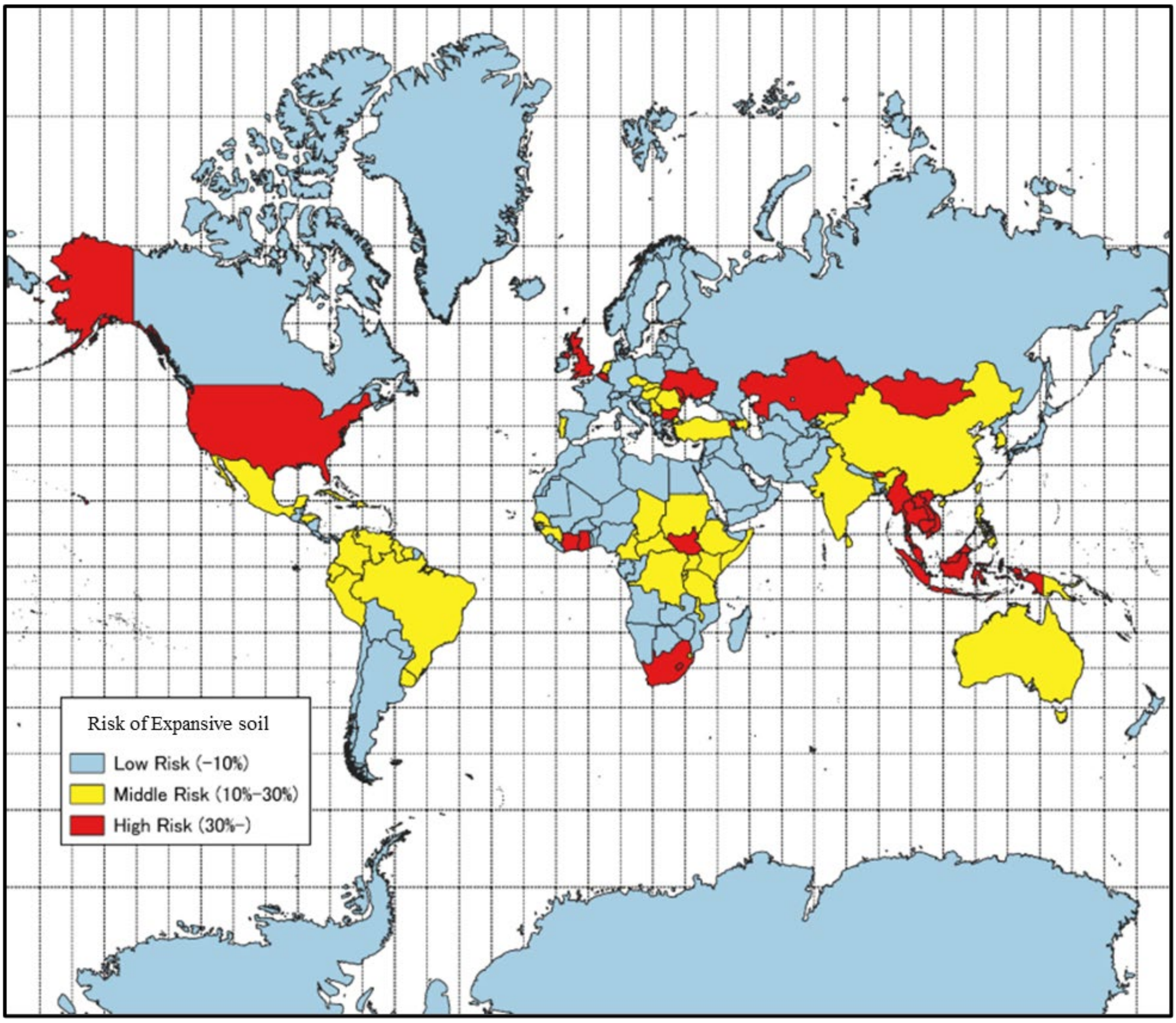


Source: JICA Study Team

Figure 2.1.31 Distribution map of expansive soil

Furthermore, based on the distribution map presented in Figure 2.1.31, the percentage of land area affected by expansive soils was calculated for each country. These percentages were then used to evaluate relative risk levels, and the results were visualized in Figure 2.1.32 as a comparative risk chart. A summary of the calculated values is provided in the accompanying table.

When planning a project in a country identified as having a moderate to high expansive soil risk, it is strongly recommended that detailed geotechnical investigations be carried out, with particular emphasis on determining the presence or absence of expansive soils at the project site. Reference to both the distribution and risk assessment figures should guide the scope and intensity of such investigations.



Source: JICA Study Team

Figure 2.1.32 Distribution risk of expansive soil

2.1.3.2 Methods for Determining Expansive Soil

(1) Identification During Site Visit

Expansive soils are often readily identifiable in the field during dry seasons by the presence of prominent surface cracks. These desiccation cracks can extend several tens of centimeters in depth and may be accompanied by distinctive microtopography such as gilgai formations or polygonal cracking.

During the reconnaissance or site inspection phase, it is important to locate an accessible exposure—such as a soil pit—near the project site where direct observation of the soil profile is possible. If no natural exposures are available, auger boring or the excavation of small test pits can be used to collect representative samples. Since soils are typically dry during the inspection period, water should be added before manual testing (e.g., palpation) to assess texture and plasticity.

In regions where Black Cotton Soils (BCS) are suspected, visual identification can be supported by recognizing their characteristic dark coloration and fine-grained consistency. When wet, expansive soils are typically very sticky and plastic. In contrast, expansive soils derived from sedimentary rocks such as clay shale may not exhibit dark coloration. In such cases, field experience is essential to correctly interpret subtle differences in color and texture.

As a simple field method to confirm suspected expansive behavior, a sample can be moistened to the point where it no longer adheres to the hand, then placed in a transparent glass container and submerged in water. Observable volume increase by the next day indicates the potential for swelling.

(2) Identification by Physical Properties

1) 1) Relevant Test Parameters

The evaluation of expansive potential based on physical properties includes the following laboratory parameters:

- Natural water content (w_0)
- Dry density (ρ_d)
- Atterberg limits:
  - Shrinkage limit (SL or w_s)
  - Plastic limit (PL or w_p)
  - Liquid limit (LL or w_L)
  - Plasticity index ($I_p = w_L - w_p$)
- Particle size distribution:
  - Fine fraction content (F_c)
  - Clay content (C_f)
- Free swell index or Differential Free Swell (DFS)

Among these, the free swell test is widely adopted in expansive soil classification and is standardized in the Indian Standard (IS), serving as a cost-effective and indicative preliminary method for expansive soil identification.

Table 2.1.8 Test criteria used to determine swelling

	Japan (JIS/JGS)	ASTM	BS	Other
Moisture content test	JIS A1203	ASTM D2216	BS 1377-2	Criteria available for each
Density test	JIS A1224	ASTM D2166	BS 1377-2	Criteria available for each
Shrinkage limit test	JIS A1209	ASTM D4943	BS 1337-T-5	Each standard is available
Plasticity and Liquidity Limit Tests	JIS A1205	ASTM D4318	BS 1337-T2, T-4	Criteria available for each
Particle size test	JIS A1204	ASTM D422	BS 1377-2	Criteria available for each
Free Expansion Index Test	-	-	-	IS: 2720 (Part40)

Source: JICA Study Team

a) Overview of the Free Swell Index (Differential Free Swell, DFS) Test

The Free Swell Index (DFS) test is a simple and widely used method for assessing the swelling potential of fine-grained soils, particularly clayey soils suspected of being expansive.

Test Procedure:

- A representative soil sample is first oven-dried and sieved through a 0.425 mm (No. 40) sieve.
- Two 100 mL graduated cylinders are prepared:
    - One filled with 100 mL of distilled water
    - The other filled with 100 mL of kerosene (used as a non-polar, non-swelling medium)
- 10 grams of the sieved soil sample is placed into each cylinder.
- The contents are stirred thoroughly to ensure the soil particles are fully dispersed and to remove trapped air.
- Both cylinders are then left undisturbed for 24 hours, allowing the soil to fully settle and expand.

Calculation:

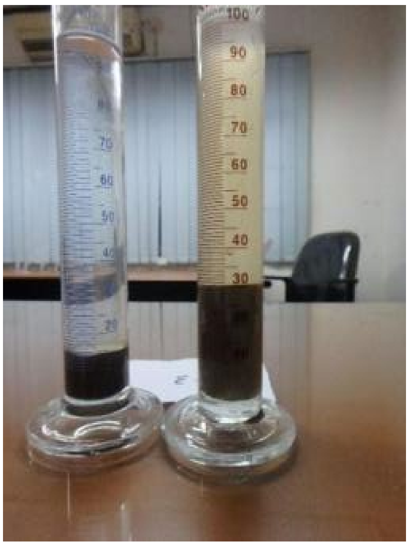
After the settlement period, the final volume of soil in each cylinder is recorded. The Differential Free Swell (DFS) is calculated using the following formula:

$$Free\ Swell\ Index(\%) = \frac{V_d - V_k}{V_k} \times 100$$

where,

V_d= Volume of sample after sedimentation in distilled water (ml)

V_k= Volume of sample after sedimentation in kerosene (ml)



Source: JICA Study Team

Figure 2.1.33 Free Expansion Rate Test

(3) Judgment by Physical Characteristics

The identification of expansive soils based solely on a single physical index is generally unreliable. Therefore, it is essential to employ a multi-parameter approach that considers a combination of physical property indicators to make a comprehensive assessment.

Among the most effective and widely used parameters are:

- Liquid limit (LL)
- Plastic limit (PL)
- Differential free swell (DFS)

Secondary indicators include:

- Colloidal content
- Natural water content (w_0)

Final classification and evaluation should be based on direct measurements of swell potential (e.g., swell ratio) and swelling pressure, where such testing is feasible.

Numerous researchers have proposed empirical methods for classifying expansive soils based on physical indices. A summary of representative formulas is provided in the Appendix.

In this section, three typical indicators are introduced:

- Swelling Ratio
- Plasticity Index (PI = LL − PL)
- Degree of Free Swell (DFS)

a) Liquid Limit

The liquid limit (LL) is one of the most frequently used indicators for estimating the potential expansiveness of fine-grained soils. Several classification systems have been proposed using threshold values of LL. A summary of representative determination methods based on liquid limit values is presented in Table 2.1.9.

Table 2.1.9 Summary and proposed determination methods based on liquid limits

Degree of expansion	Ladd.	IS 1498	Snethen	Williams	Neil.	Chen	Chen
	1961	1970	1977	1977	1980	1975, 1987	1988+M
Low	20~35	20~ 35	<50	<50	<50	20~ 35	<30
Medium	35~50	35~ 50	50~ 60	50~ 60	50~ 60	35~ 50	30~ 40
High	50~ 70	50~ 70	>60	>60	>60	50~ 70	40~ 60
Very high	70~ 90	70~ 90					>60

Degree of expansion	Liu Tehong	Zheng Jiaqi	Li Shenglin	Public road expansion soil process	Suggested. Judgment method
	1997	1999	2003	2009	
Low	15~ 45	40~ 55	40~ 45	<40	30
Medium	45~ 50	55~ 65	45~ 50	40~ 48	30~40
High	>50	>65	50~ 55	>48	40~60
Very high			>55		>60

Source: JICA Study Team

b) Plasticity index

The plasticity index is the most used parameter in the determination of expansive soils and has been proposed by many references. Table 2.1.10 shows examples of determination methods based on the plasticity index.

Table 2.1.10 Example of determination method based on plasticity index

Degree of expansion	Zheng Jiaqi	Claudial	Bekkouche	Li Shenglin	CMC	CMC	Transportation Department Standard	ACPA
	1999	2000	2001	2003	2004	2004	2004	2008
low (position)	<20	<12	<18	<18	<18	<15	15~ 28	< 8
about medium	20~ 26	12~ 35	18~ 22	18~ 25	15~28	15~28	28~ 40	15~ 28
high	>26	35~ 45	22~ 35	25~ 35	25~41	28~40	>40	24~ 41
Very high		>45	>35	>35	>35	> 40		>35

Source: JICA Study Team

c) Free expansion rate

The free expansion coefficient is the second most commonly used index after the plasticity index. Table 2.1.11 shows an example of a determination method based on the free expansion coefficient.

Table 2.1.11 Example of determination method based on free expansion ratio

Degree of expansion	IS1498	IS1498	Liu Tehong	Sridharan	Li Shenglin	CMC
	1970	1997	1997	2000	2003	2004
low (position)	<50	<20	40~65	<50	40~55	< 40
about medium	50~100	20~35	65~90	50~ 100	55~70	40~ 60
high	100~200	35~50	>90	100~ 200	70~85	60~ 90
Very high	>200	>50		>200	>85	> 90

Source: JICA Study Team

d) Combination of Proposed Decision Indicators

It is generally recommended to use multiple indicators to assess the swelling potential of soils. Various combinations and threshold values have been proposed by researchers. Table 2.1.12 presents representative criteria, primarily based on Black Cotton Soils (BCS). For highly expansive soils, it may be appropriate to define separate classification thresholds.

Table 2.1.12 Proposed Swelling potential Determination Method

Degree of expansion	Liquid Limit (LL, %)	Plasticity Index (Ip, %)	Free Swell Index (FSI, %)	Colloidal Content (CC, %)	Natural Moisture Content (W_0, %)
Low	~30	<10	<20	15	>35
Medium	30–40	10–20	20–35	15–20	25–35
High	40–60	20–35	35–50	20–28	15–25
Very High	>60	>35	>50	>28	<15

Source: JICA Study Team

e) Judgment by Diagram

Graphical determination methods offer the advantage of using two or more parameters simultaneously, generally improving reliability over single-parameter approaches. Widely used diagrams include Figure 2.1.34 and Figure 2.1.35.

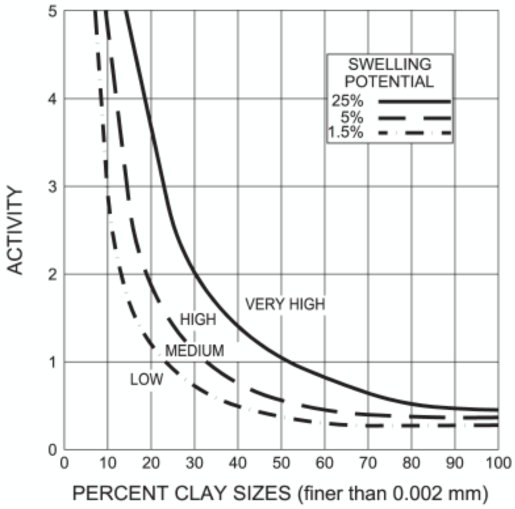


FIGURE 9.2. Swelling potential for compacted clays based on activity and percent clay (Seed, Woodward, and Lundgren 1962).

Source: Foundation Engineering for Expansive Soils, J.D. Nelson et al., Wiley, 2015

Figure 2.1.34 Determination by clay content and activity (Seed et al., 1962)

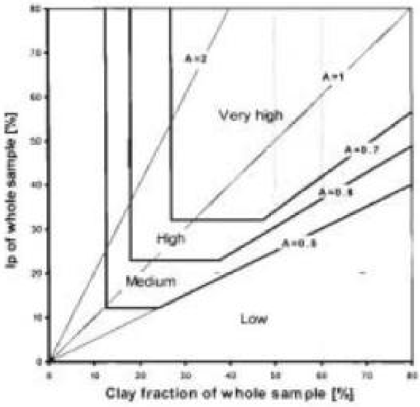


Figure 2.8 Classification chart after Williams and Donaldson (1980).

Source: A Universal Method for Assessing Intrinsic Expansiveness of Soils, Kebreab Berhane Habte, 2004

Figure 2.1.35 Determination by clay content and plasticity index (Williams and Donaldson, 1980)

Comprehensive judgment should always incorporate additional indicators in conjunction with graphical methods.

(4) Determination by Clay Minerals

The identification of expansive soils can also be performed through mineralogical analysis, particularly by detecting smectitic clay minerals such as montmorillonite. This can be achieved through crystal structure characterization or chemical analysis.

It is important to note that montmorillonite may also be present in dispersive soils, and conversely, not all expansive soils contain montmorillonite. Thus, interpretation should be made with caution.

Common methods for clay mineral identification include:

- X-ray Diffraction (XRD): Determines basal spacing based on diffracted X-rays.
- Differential Thermal Analysis (DTA): Identifies minerals by comparing thermograms with known standards, leveraging characteristic endothermic/exothermic reactions.
- Electron Microscopy: Provides direct observation of clay particle size and morphology for qualitative identification.

(5) Determination by Chemical Analysis

Chemical indicators used in the identification of expansive soils include:

- Cation Exchange Capacity (CEC)
- Specific Surface Area (SSA)
- Total Potassium (TP)

Details of these methods are provided in the Appendix.

Because expansive and dispersive soils often share similar chemical properties, supplementary indicators must be used to distinguish between them. Notably, these soils behave differently depending on the pH of the environment. Expansive soils tend to exhibit higher swelling potential in neutral to slightly alkaline conditions, whereas dispersive soils are more reactive under strongly alkaline conditions.

Table 2.1.13 Behavior of Expansive and Dispersive Soils as a Function of Alkalinity (pH)

pH (Acidity Level)	Environmental Condition	Expansive Soil	Dispersive Soil
<5	Acidic	Reduced swelling: clay particles agglomerate easily	Difficult to disperse
6–7	Slightly acidic to neutral	Swelling begins but remains moderate	Dispersion is somewhat suppressed
7–9	Neutral to slightly alkaline	Maximum swelling	Increased tendency to disperse
9–10	Alkaline	Continued swelling of Na^{+}-type montmorillonite	Maximum dispersibility
>10	Strongly alkaline	Reduced swelling of Ca^{2+}-type montmorillonite	Very easy to disperse

***Source**: JICA Study Team*

2.1.3.3 Swelling Test by Mechanical Methods

Three principal mechanical testing methods are used to evaluate expansive soils: the **c**onsolidation test, the COLE (Coefficient of Linear Extensibility) test, and the swelling index (EI) test. This section focuses on the consolidation test, which is widely used as a standard method for determining swelling characteristics.

(1) Evaluation by Consolidation Test

The consolidation test is extensively used worldwide due to its relative simplicity and the widespread availability of testing equipment. The most common procedure is the Consolidation-Swelling (CS) test, in which a specimen is first subjected to a specified vertical stress using a conventional consolidation apparatus, followed by inundation under the same stress condition. The swelling strain ε_s or swelling potential S_p is measured as the vertical strain induced by wetting.

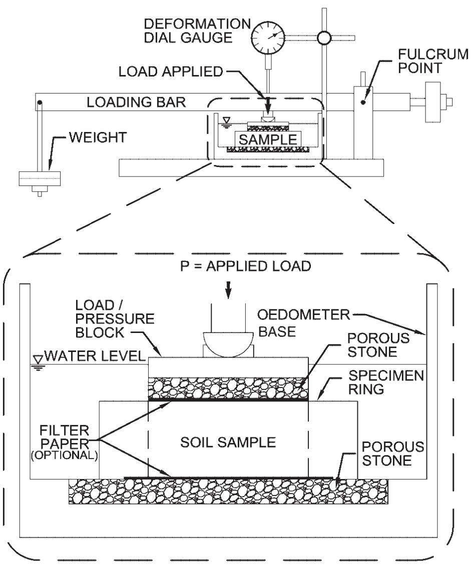
Once swelling stabilizes, additional loading is applied to restore the specimen to its original height. The required stress is recorded as the swelling pressure σ_{cs}'' or p_s.

Another standard method is the Constant Volume (CV) swelling test, in which a specimen is also preloaded and then inundated. The load required to completely prevent volume change during wetting is recorded as the constant volume swelling pressure σ_{cv}''.

Figure 2.1.36 presents a schematic diagram of the consolidation test apparatus, while Figure 2.1.37 illustrates the relationship between swelling rate and swelling pressure based on test results.

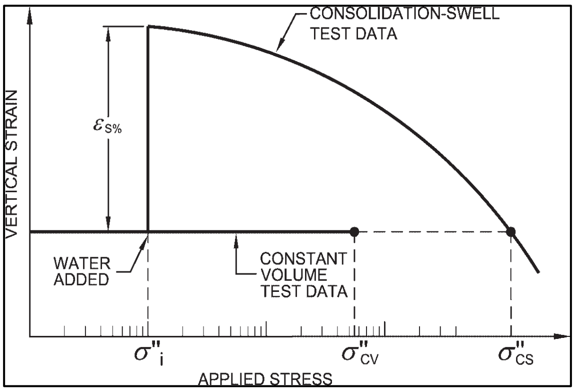
The standard method for evaluating swelling potential is defined in ASTM D4546, which is specifically designed for expansive soils and differs from the general consolidation testing procedure under ASTM D2435/D2435M. In the CS test, the swelling strain ε_s varies depending on the applied pre-wetting stress $\sigma(i)''$, so this initial stress must be considered in design applications. In contrast, the CV test yields a swelling pressure σ_{cv}' that is independent of the initial stress.

It should be noted that ASTM D4546 emphasizes the following:
"The accuracy of this test method depends on the competence of the personnel conducting the tests and the suitability of the equipment and facilities used."
Therefore, testers must be properly trained in the underlying engineering principles and the correct interpretation of results.



Source: Foundation Engineering for Expansive Soils, J. D. Nelson, K. C. (Geoff) Chao, D. D. Overton, E. J. Nelson, John Wiley & Sons (2015)

Figure 2.1.36 Schematic diagram of the Oedometer



Source: Foundation Engineering for Expansive Soils, J. D. Nelson, K. C. (Geoff) Chao, D. D. Overton, E. J. Nelson, John Wiley & Sons (2015)

Figure 2.1.37 Swelling rate, swelling pressure

Table 2.1.14 Criteria for Determining Swelling Potential Using a Consolidation Tester

Degree of expansion	Swelling rate (%)			Swelling pressure (kPa)	
	disturbance	medium	large	small	large
Low	<0.5	<4	<10	<50	<100
Medium	0.5~ 1.5	4 8~	10~ 20	50~100	100~250
High	1.5~ 4.5	8~ 16	20~ 30	100~250	250~500
Very high	>4.5	>16	>30	>250	>500

Note: Swelling characteristics vary depending on regional soil types. Final evaluations should consider allowable displacement and loading conditions of the intended structure.

Source: JICA Study Team

2.1.4 Considerations for the Design of Countermeasure Works and Selection of Countermeasure Methods

> If expansive soil is determined to be present during the planning and investigation phase, countermeasures are considered to minimize the risk of expansive soil behavior during and after construction. Various countermeasure methods are adopted based on various principles, such as surcharging, replacement, improvement by chemical or thermal treatment, and control of moisture content and compaction. In selecting a countermeasure method, the relevant standards of the target country or countries, existing literature, and case studies in the target area should be consulted to select a countermeasure method that is appropriate for the target site.
>
> In design, specific values for the thickness of the replacement layer, type and mixing ratio of the improvement material, water content ratio, degree of compaction, etc., should be considered and set according to the selected countermeasure work.
>
> In the construction phase, it is necessary to take sufficient care to minimize risk in accordance with the design drawings and specifications, while conducting quality control in accordance with the specifications and in consideration of the purpose of the countermeasure construction. In addition, since the characteristics of expansive soil vary widely from region to region, and depending on its characteristics, the expected sufficient countermeasure effect may not be achieved, it is desirable to incorporate test construction into the project if there are few examples of such countermeasures in the target area, or if there are many problems caused by expansive soil, or if there is a high risk.
>
> The following is a list of items to be considered in the selection of countermeasure works, the design of each countermeasure work, and items to be considered and taken into account during construction.

［Explanation.]

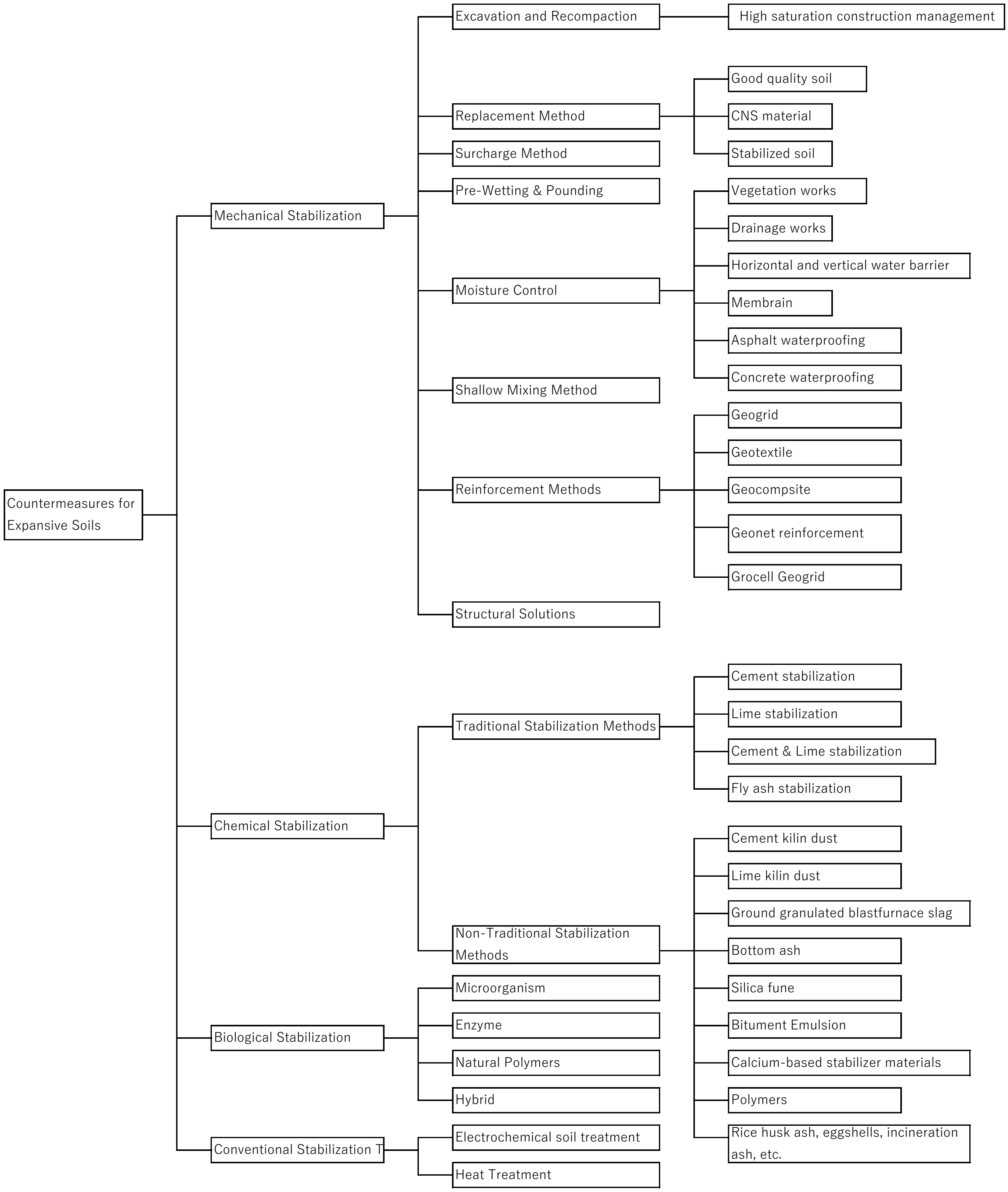
2.1.4.1 Considerations in the Design and Selection of Countermeasure Methods

When designing countermeasure works for expansive soils, it is essential to incorporate local experience and engineering judgment regarding the site-specific soil conditions, the limitations of each countermeasure method, and the suitability of construction techniques. The following factors should be taken into account when selecting the appropriate countermeasure:

- Project scale
- Phasing of construction funding (e.g., initial investment required for land reclamation or pond treatment)
- Nature and use of the facility (e.g., airport runway vs. secondary road, allowable stress variations, and maximum permissible volumetric change)
- Cost-effectiveness in comparison with alternative construction methods

The typical countermeasures applied in expansive soil projects are illustrated in Figure 2.1.38, and their respective advantages and disadvantages are summarized in Table 2.1.15. Additionally, key considerations for selecting suitable countermeasures are also presented in the same table.

It is strongly recommended to review relevant case studies—both successful applications and failures—within the target country or region to confirm feasibility. This helps ensure that the selected countermeasure is not only technically effective but also practical under local construction conditions.



Source: JICA Study Team

Figure 2.1.38 Countermeasure method for expansive soil

Table 2.1.15 Countermeasure Methods Applied to Expansive Soils

Stabilization Method	Treatment Method Overview	Advantages	Drawbacks
In-situ Excavation and Re-compaction	Soils are compacted at moisture contents above optimum to reduce swelling potential. Standard compaction equipment and controls are applied to achieve target density.	Utilizes in-situ material; no replacement cost Results in relatively impermeable layers that limit water infiltration. Reduces swelling potential without introducing excess water	Low-density compaction may reduce bearing capacity Less effective on highly expansive soils Requires strict quality control
Replacement Method	Expansive soil is excavated and replaced with non-expansive materials to a depth sufficient to prevent uplift. Chen (1988) recommends 1.0–1.3m minimum.	Improved support through substitution Simple and fast to construct Effective for many applications	Impervious backfill preferred but expensive Required depth may be impractical Risk of water ingress during construction Effectiveness depends on CNS material availability
CNS Cushion Layer	Commonly used in India, this method places a Cohesive Non-Swelling (CNS) soil layer between the structure and expansive soil. The CNS layer prevents deep crack penetration and moisture infiltration even in dry seasons.	Cost-effective if CNS is locally available Quick and easy to install Requires thinner layers than full replacement Reduces swelling pressure on structures	High transportation costs if CNS sources are distant Not all regions have local CNS deposits
Surcharge Loading	A preload is applied to counteract swelling pressure, particularly where swelling is relatively small.	Economical and easy to apply Effective for low swelling pressures Fill materials can vary (granular, impermeable, etc.)	Ineffective for high swelling pressures Repeated moisture changes may reduce long-term effectiveness
Pre-wetting / Ponding	Moisture content is increased before construction by ponding or infiltration via trenches or drains. Intended to pre-swell soils before loading.	Effective in soils with high permeability or fissures Reduces post-construction swelling where sufficient infiltration occurs	May require several years Strength reduction or cracking may occur Limited to shallow depths Risk of delayed swelling due to water redistribution
Chemical Stabilization	Typically uses lime (3–8%), cement (2–6%), or less commonly, salts, fly ash, or organics. Surface mixing (~30 cm) followed by sealing, curing, and compaction. Lime slurry injection is also practiced. Most effective for high-plasticity clays.	Applicable to most fine-grained soils Reduces plasticity and swell potential	Chemical compatibility issues may arise Health, safety, and environmental risks (e.g., quicklime reactivity) Effectiveness decreases at low temperatures
Moisture Control	Horizontal or vertical barriers (e.g., membranes, cutoffs) are installed to prevent water infiltration into expansive soils.	Cost-effective when localized or targeted Minimizes moisture variation	Expensive for large-scale applications (e.g., roads, airfields); Ineffective if water enters from outside protected zones; High-performance barriers are costly

Source: JICA Study Team

Table 2.1.16 Considerations for Successful Application of Countermeasures in Expansive Soils

Countermeasure	Main Considerations
Replacement Method	Use economical, non-expansive, impermeable fill. Granular fill requires careful drainage control. Sub-excavation may be needed. Use vertical/horizontal membranes for protection. Sprayed asphalt membranes are effective in highways.
Remolding and compaction	Best for soils with low expansion potential, high dry density, and low natural moisture. Lime treatment improves performance if reactive. Without lime, lower bearing capacity is expected. Quality and moisture control are essential, especially for deep active zones.
Surcharge loading	Suitable if swell pressure is low and deformation is tolerable. Requires soil testing to define active zone and pressures. Drainage control is important. Moisture can migrate both vertically and horizontally.
Pre-wetting	May require up to a year to raise moisture. Vertical sand drains help. Works better on fissured soils. Moisture must reach 2–3% above plastic limit. Surfactants may help percolation. Risk of deeper swelling if excess water remains. Lime treatment after pre-wetting improves workability and strength. Surface must be protected.
Lime Stabilization	Requires >70°F (21°C) for 10–14 days. Organics, sulfates, iron may retard reaction. Soil should be tested for lime reactivity and proper dosage. Typical depth is 12–18 in., up to 2 ft with large equipment. Excess water needed; delay after application improves compaction. Quality control is critical. Prevent leaching from groundwater. Deep injection has limited penetration; fissures help dispersion.
Cement Stabilization	4–6% Portland cement reduces volume change. Similar to lime but less delay. More effective in non-lime-reactive soils. May yield higher strengths. Cracking potential must be evaluated.
Salt Treatment	Only $NaCl$ and $CaCl_2$ are economically viable. Easily leached; treatment may lack permanence. $CaCl_2$ requires ≥30% relative humidity. Useful for frost heave and high-sulfur soils.
Fly Ash	Barriers must extend far enough to block horizontal moisture. Joints must be sealed, sloped away from the structure. Use durable, non-degradable materials. Vegetation must be kept away.
Organic Compounds	Spray/injection ineffective due to poor diffusion. Many are water-insoluble and react irreversibly. Generally less effective and less economical than lime.
Horizontal Barrier	Extend barrier far enough from the structure. Attach securely, seal joints, slope for drainage. Use durable materials. Keep plants away. Protect edges from surface water.
Asphalt	In highways, continuous membranes over subgrade and ditches. Easier to repair than concrete. Enhances slab and pavement strength.
Rigid Barriers	Reinforce sidewalks. Use flexible joints to connect to foundations. Inspect regularly for cracks and leaks.
Vertical Barrier	Extend to at least half the active zone. Use impervious backfill. Effective types: capillary barriers, lean concrete, asphalt, polyethylene, semi-hardening slurries. Trenching machines preferred.
Membrane encapsulated soil layers	Seal joints carefully. Use durable membranes. Control first soil placement to avoid damage.

Source: Expansive Soils: Problems and Practice in Foundation and Pavement Engineering, John D. Nelson & Debora J. Miller, John Wiley & Sons, Inc. (1992) - The JICA study team has simplified the content.

2.1.4.2 Related Standards for Countermeasure Construction

There are limited formal standards that prescribe detailed design methodologies specifically for expansive or other problem soils. However, a few countries and organizations have developed guidelines relevant to construction on such soils:

- China has published standards and technical guidelines for highways, railways, and high-speed rail systems.
- The International Building Code (IBC), particularly Chapter 18 *Soils and Foundations*, provides general guidance on geotechnical issues including swampy soils, though it lacks prescriptive design methods for expansive soils.
- Indonesia has established practical standards for the use of geomembranes in controlling moisture in swampy soils, offering a strong example of applied engineering for moisture-sensitive ground conditions.
- The U.S. Army Corps of Engineers issued a technical manual for foundations in expansive soils in 1983 (TM 5-818-7), though it is now considered outdated.
- For modern and practical applications, it is advisable to consult commercially available geotechnical reference books.

Table 2.1.17 lists examples of national and regional design criteria and standards for expansive soils. Table 2.1.18 provides a selection of key reference texts related to expansive soil engineering.

Table 2.1.17 Examples of Design Criteria for Expansive Soils

Country/Region	Standards and Guidelines
International	International Building Code, Chapter 18: Soils and Foundations
India	IS 9451:1994 – Guidelines for Lining of Canals in Expansive Soils Expansive Soil Guidelines
Indonesia	Pd T-11-2004-B – Guidelines for Construction and Buildings: Handling of Expansive Soils Using Geomembranes as Vertical Moisture Barriers Issued by: Ministry of Settlements and Regional Infrastructure
Ethiopia	Geotechnical Design Manual (2013), Site Investigation Manual (2013), Ethiopian Roads Authority
Kenya	Pavement Design Guideline for Low Volume Sealed Roads, Ministry of Transport, Infrastructure, Housing and Urban Development (2017)
Tanzania	Field Testing Manual (2003), Pavement and Materials Design Manual (1999), Standard Specification for Road Works (2000), Tanzania National Roads Agency
U.S. Army	TM 5-818-7 – Technical Manual: Foundations in Expansive Soils, Department of the Army (1983)
Australia	WQ35 – Best Practice Guidelines for Paving Materials on Expansive Soils in Western Queensland (2014) SWQ37 – Drainage Structures on Expansive Soils
China	Highway Expansion Earthwork Schedule, Expansive Soil Engineering in Highway (2009) Railway Weakly Expanding Soil Road Base Construction Guidelines (2012) 200 km/h Railway Embankment Improvement Manual (2007)
New Zealand	NZS3604 – Identification and Assessment of Expansive Soil in New Zealand
United States	Foundation Requirements on Expansive Soil, Los Angeles County (1983, 2009) Expansive Soil Foundation Design, County of San Diego (2023) Expansive Soils Policy, Roanoke County, VA Las Vegas & Henderson Building Code (2021), Ch. 18

***Source**: JICA Study Team*

Table 2.1.18 Examples of Reference Books on Expansive Soils

Reference Title	Publisher
2021 International Tiny House Provisions: Code, Explanation and Standards (R403.1.8: Foundations on Expansive Soils)	ITHP
Expansive Soils: Problems and Practice in Foundation and Pavement Engineering (1992) – John D. Nelson and Debora J. Miller	John Wiley & Sons
Foundation Engineering for Expansive Soils (2015) – John D. Nelson, Kuo Chieh (Geoff) Chao, Daniel D. Overton, Erik J. Nelson	Wiley
Foundations on Expansive Soils (1975) – Fu Hua Chen	Elsevier Scientific Publishing
Textbook of Soil Mechanics and Foundation Engineering (2012), Chapter 24: *Foundations on Collapsible and Expansive Soils* – V.N.S. Marthy	CBS Publishers
Construction of Buildings on Expansive Soils (1991) – E.A. Sorochan	CRC Press

***Source**: JICA Study Team*

2.1.5 Consultant and Contractor Business Considerations

At the planning, investigation, and design stages, the consultant shall be responsible for accurately identifying the distribution of expansive soils at the project site. Investigations and laboratory/field testing should be conducted with the objective of minimizing geotechnical risk associated with expansive soil behavior. Where necessary, appropriate countermeasures shall be planned and designed. These countermeasures must be clearly reflected in the bidding documents, allowing contractors to estimate the required costs based on geotechnical risk, necessary testing, quality control procedures, and construction considerations.

During the construction supervision phase, the consultant must ensure that the countermeasures are implemented according to the project specifications and verify quality and performance through both in-situ and laboratory-based testing.

The contractor, for their part, must possess a clear understanding of the nature and engineering risks associated with expansive soils. Construction works shall be carried out with appropriate consideration of these soil characteristics, in accordance with the contract documents, while also performing necessary testing and quality control procedures.

［Explanation］

2.1.5.1 Notes on the Preparation of Bidding Documents

When expansive soils are identified or suspected within the project area, the following considerations should be addressed in the preparation of bid and contract documents:

- If surrounding site investigations indicate the possible use of expansive soil as fill material, the quality control testing methods, reference values, and test frequencies required to accurately determine expansiveness at the site shall be clearly specified in the technical specifications.
- If expansive soil is likely to be encountered in pavement subgrades or building/structure foundations, provisions must be included in the technical specifications to mitigate unforeseen risks. For example, this may include requirements for photographic records of exposed subgrade surfaces and procedures for on-site verification and approval prior to proceeding with construction.
- Since technical knowledge related to expansive soil countermeasures and construction practices is less comprehensive than that for conventional soils, the planning and design of countermeasures must be preceded by thorough research, with due consideration given to site-specific testing and constructability.
- Where the replacement of expansive soil with high-quality backfill is proposed, the extent and

depth of replacement shall be clearly indicated on the construction drawings. The technical specifications shall include measures to mitigate water-related risks, along with material quality criteria and compaction standards for backfilling.

- Where soil improvement materials (e.g., lime, cement, fly ash) are to be used, the technical specifications shall clearly define the type of material, mix ratio, testing requirements, and acceptance criteria for field application.

2.1.5.2 Considerations for Quality Control During Construction

Engineers engaged in construction management must have a thorough understanding of the characteristics of expansive soils—particularly their tendency to undergo volumetric changes (swelling and shrinkage) due to cyclic fluctuations in surface and groundwater levels. Appropriate consideration should be given at each construction stage based on this understanding.

It is also essential that the physical characteristics of the expansive soil distributed at the site—such as color, texture, and plasticity—be confirmed and understood before construction begins. This allows engineers to visually and manually identify expansive soils accurately during field operations.

Key considerations for quality control during construction involving expansive soils include the following:

- Monitoring groundwater influence: Unexpected variations in the groundwater regime can induce expansive behavior and lead to structural damage. Particular attention must be paid to local water sources, such as springs, buried utility lines, or vegetation root systems, that may contribute to localized moisture fluctuations. Where such risks are identified, appropriate mitigation measures must be implemented.
- Dynamic observation during construction: Given the time-dependent behavior of expansive soils, it is advisable to install instrumentation—e.g., settlement plates or markers—on subgrade surfaces to monitor deformation during and after construction. If measurement data indicate expansive soil movement, countermeasures should be evaluated and applied as necessary to minimize structural impact.
- Construction documentation and data recording: Maintaining a high-frequency record of construction activities is recommended, especially in areas where expansive soils are present. Detailed documentation of site conditions, material properties, and construction procedures will support the planning of effective countermeasures in the event of unforeseen behavior. Furthermore, compiling and sharing this information—through quality control reports, internal archives, or academic publications—can contribute to future risk mitigation and the advancement of expansive soil research.

2.1.6 Actions to Be Taken at the Maintenance and Management Stage

> In areas where expansive soils are distributed, appropriate maintenance and management measures must be implemented to ensure that constructed structures continue to perform their intended functions. Maintenance activities—including monitoring, inspection, maintenance, repair, and restoration—should be carried out as necessary, based on the records from the investigation, design, and construction phases.

[Explanation]

2.1.6.1 Objectives of Maintenance

The primary objective of maintenance is to ensure that structures (such as roads, canals, and buildings) continue to function effectively and safely after construction is completed.

As described in Section 2.1.2 “Examples of Problem Soils Encountered in Past Construction Projects”, expansive soils can cause various forms of structural damage, including:

- Uplift or landslides of embankments
- Pavement heaving and cracking
- Deformation and cracks of buildings
- Surface and slip failures in cut or fill slopes
- Damage to buried structures such as culverts and channels

Deformations caused by expansive soils should be identified as early as possible, and appropriate remedial actions should be taken without delay to prevent progression and ensure structural integrity.

2.1.6.2 Key Points for Maintenance

The deformation behavior associated with expansive soils varies greatly. Damage may occur immediately after construction or emerge years later as a result of environmental changes. Even after countermeasures are implemented, new moisture sources—such as leakage, poor drainage, or vegetation—can trigger swelling in previously stable areas.
In particular:

- Large trees planted near structures may alter the soil moisture balance through root absorption, resulting in localized drying and subsidence.
- Conversely, tree removal can lead to a sudden increase in soil moisture, inducing swelling and uplift due to the loss of evapotranspiration effects.

This is especially critical in road infrastructure, where surface deformations such as longitudinal cracking can impair function. Once signs of expansive soil-related damage are detected, the following actions are essential:

- Investigation of the current deformation state
- Review of records from investigation, design, and construction
- Forecasting of potential deformation progression
- Planning and execution of appropriate repair strategies

2.1.6.3 Inspection and Survey

Routine inspection is essential to detect structural deformations in their early stages—before they result in serious damage—and to assess the need for countermeasures or repairs.
Inspectors must be aware of critical locations and risk indicators based on prior case histories involving expansive soils. For example:

- Road pavements should be inspected for cracking caused by subgrade soil expansion/contraction.
- Embankments should be checked for longitudinal cracks, which may occur due to uneven lateral swelling.

Prior to project handover—particularly in ODA (Official Development Assistance) projects—daily inspection and monitoring requirements should be clearly documented and communicated to local operators. Special attention should be given to high-risk zones and maintenance planning should reflect site-specific geotechnical conditions.

2.2 DISPERSIVE SOIL

2.2.1 Summary

Dispersive soils are defined as soils in which clay particles readily disaggregate and disperse into suspension upon contact with water. Unlike typical cohesive soils, dispersive soils exhibit minimal electrochemical attraction between particles, causing individual clay particles to behave independently in water without forming inter-particle bonds or aggregates.

These soils are difficult to identify visually or by conventional physical indices such as Atterberg limits or particle size distribution. Accurate identification requires specific tests such as the pinhole test and the double hydrometer test.

Researches on dispersive soils have primarily focused on piping phenomena in earth embankments and dams, where internal erosion can cause catastrophic structural failures. While surface erosion and cavity formation (e.g., “dragon holes” reported in Cambodia) also occur in slopes and roadways, these mechanisms have been less frequently studied. Due to the severe consequences of dam and levee failures, academic efforts have concentrated on the physicochemical mechanisms of dispersion, whereas engineering solutions and countermeasure research remain relatively underdeveloped compared to those for expansive soils.

To mitigate risks in areas with dispersive soils, it is essential to understand the fundamental dispersion mechanisms and conduct thorough site investigations, planning, design, and construction in accordance with geotechnical best practices.

［Explanation］

2.2.1.1 Characteristics of Dispersive Soil

(1) General Characteristics

Key features of dispersive soils include:

- Clay particles disaggregate and disperse into suspension upon contact with water.
- Inter-particle repulsive forces exceed attractive (cohesive) forces, leading to the breakdown of soil structure and the formation of colloidal suspensions.
- Dispersion occurs even in still water, rendering the soil highly susceptible to erosion and piping.
- No threshold velocity is required for erosion; particle detachment can occur regardless of flow strength.

Dispersion is fundamentally a physicochemical process in which the balance of forces between clay particles is disrupted. When the repulsive electrostatic forces dominate over the van der Waals and other attractive forces—especially in the presence of low ionic strength water—individual particles repel one another and enter suspension. In contrast, non-dispersive soils exhibit structural cohesion that resists erosion unless exposed to sufficiently strong flowing water.

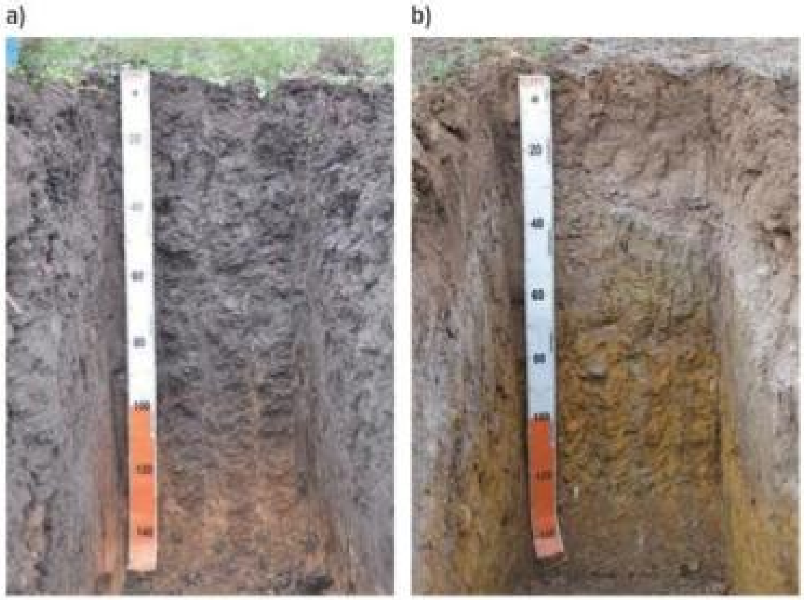
Dispersive soils often contain moderate to high clay fractions, but total clay content alone is not a sufficient indicator of dispersibility. Even soils with less than 10% clay may lack enough colloidal particles to initiate piping, while some high-clay soils remain stable under hydraulic loading.

One of the primary contributors to dispersion is a high sodium concentration in the soil's pore water, which can reach levels of up to 12%. Excessive sodium leads to an increase in the diffuse double layer thickness surrounding clay particles, reducing inter-particle attraction and facilitating disaggregation in water. Dispersive clays can be more erodible in still water than in flowing water due to their fine particle size and physicochemical behavior.

In Australia, dispersive soils are categorized within the Australian Soil Classification System under two main soil orders:

- Gray Vertosols with sodic subsoils
- Sodosols (sodic soils with alkaline, abruptly changing subsoil horizons)

Soil Type	Description
Gray Vertosols	Swelling clays prone to cracking; sodic characteristics present in the subsoil layers
Yellow Sodosols	Strongly sodic soils with alkaline profiles and sharp textural boundaries



a) Gray Vertosols with sodic subsoil.

Vertosols are crack-prone clays.

b) Yellow Sodosols; Sodosols are sodic soils with alkaline and rapidly changing layers.

Source: Dispersive Soil Manual Managing Dispersive Soils practicalities and economics - Northern Region, David McKenzie, Alisa Bryce (2023).

Figure 2.2.1 Australian dispersive soil

(2) Origin and Parent Material of Dispersive Soils

The dominant clay minerals found in dispersive soils include:

- Mica – Associated with the formation of slip surfaces.
- Kaolinite – Common in highly weathered tropical soils; exhibits weak inter-particle bonding.
- Vermiculite – A 2:1 clay mineral contributing to structural instability.
- Montmorillonite – Highly expansive and strongly involved in dispersion phenomena.

These minerals play a significant role in influencing the engineering behavior of soils. In particular, mica is thought to contribute to the development of failure surfaces due to its platy structure and weak bonding. The type of clay mineral, along with the orientation of clay particles, directly impacts residual strength and overall soil stability.

Clay mineralogy varies with pedogenic processes and environmental conditions, which in turn influence soil classification and spatial distribution. For instance:

- Kaolinite is prevalent in deeply weathered tropical soils, such as Oxisols and Ultisols.
- In addition to chemical reactivity, clay minerals also affect the physical properties of soils, including water retention, permeability, and interaction with biological activity.

Dispersive soils have been identified in various geological and climatic settings, with typical parent materials and influencing conditions summarized as follows:

- Low-lying areas with active seepage and high Sodium Adsorption Ratio (SAR) in percolating water. These zones are particularly vulnerable when Weinert's climatic N values range from 2 to 10. Soils derived from granite tend to exhibit high Exchangeable Sodium Percentage (ESP), and their primary minerals (e.g., orthoclase, albite) are low in Ca^{2+} and Mg^{2+}, contributing to elevated SAR and dispersibility.
- Soils with high illite content and other 2:1 clay minerals, particularly in transported soils. Regions with climatic N values of 2–10, such as those containing Cretaceous mudstones, the Upper Beaufort Group, and the Molteno Formation of the Karoo Supergroup, are often associated with dispersive soils, especially in lowland settings.
- Arid regions with $N > 10$: Although high SAR values exist in saturated extracts, the presence of free salt initially inhibits dispersion. However, once leaching occurs and salts are removed, dispersibility may develop.
- Soils derived from granite or mudstone may exhibit dispersive behavior even when $ESP < 5$, possibly due to elevated Mg^{2+} concentrations relative to Ca^{2+}.
- Soils high in montmorillonite tend to exhibit expansive behavior, whereas those with high Na^{+} concentration are prone to dispersion.

(3) Dispersion Mechanism

The fundamental mechanism of dispersion in clay soils involves the breakdown of inter-particle bonding due to physicochemical imbalances, as outlined below:

- Thickening of the diffuse double layer surrounding clay particles enhances inter-particle repulsion.
- The dispersion process is influenced by a combination of factors:
  - ➢ Soil structure and pore geometry
  - ➢ Type and proportion of clay minerals
  - ➢ Moisture content, organic matter, and temperature
  - ➢ Thixotropic properties and the ionic composition of the pore solution
- Surface swelling induced by hydration reduces inter-particle cohesion, initiating erosion and dispersion.
- Dispersion can occur even in stagnant water, distinguishing it from mechanical disintegration or particle crushing.
- While high Na^{+} content promotes dispersion, montmorillonite presence is often necessary for full expression of dispersive behavior.

2.2.2 Examples of Problem Soils Encountered in Past Construction Projects

Dispersive soils have been implicated in various geotechnical failures affecting infrastructure. Notable examples include:

- Piping and structural cracking in earth dams
- Cave-ins and sinkholes (often referred to as "dragon holes") along roads and levees
- Progressive slope erosion

These problems often arise when dispersive soils are used in hydraulic structures, particularly where topographic modification, surface runoff concentration, or groundwater fluctuations—such as those induced by heavy rainfall—alter the hydraulic regime.

While damage from dispersive soils may initially appear minor and pose only routine maintenance concerns, internal erosion can develop insidiously. Without early detection, minor surface erosion may evolve into severe structural degradation. Therefore, in regions with suspected or confirmed dispersive soils, it is essential to adopt comprehensive investigation planning, cautious design, proper construction execution, and long-term maintenance protocols.

This section introduces representative case studies to support the evaluation of risk and development of appropriate countermeasures in target project areas.

［**Explanation**］

2.2.2.1 Case Study: Internal Erosion Failure and Damage

Dispersive clays are typically characterized by low to very low permeability. Under normal conditions, the seepage velocity is insufficient to initiate particle movement—even under relatively high hydraulic gradients. However, the presence of cracks, joints, or construction defects can provide preferential flow paths through which dispersed clay particles are mobilized.

Several conditions contribute to this mechanism:

- Dispersive clays exhibit dry cracking behavior, especially during moisture fluctuations.
- Settlement differentials or hydraulic fracturing can induce cracks in dams.
- Inadequate compaction, particularly near conduits, joints, or heterogeneous interfaces, increases the likelihood of internal erosion initiation.

When such conditions exist, piping failure can develop rapidly, even under low hydraulic head differences. Once water infiltrates these openings, the clay disperses into suspension, leading to progressive internal erosion and eventual failure of the structure.

Figures 2.2.2 and 2.2.3 illustrate examples of dam failure due to piping and tunnel erosion in dispersive clay environments.

Figure 2. Failure of embankment constructed on dispersive soil (Missipi, USA)

Source : STABILIZATION OF DISPERSIVE SOIL BY USING FLY ASH, Md. Omar Faruk, Mohammad Shariful Islam, Mohammad Ziaul Hoque, Marzia Ashraf Shomo, 2019

Figure 2.2.2 Dam collapse due to piping

Figure 5. Piping failure or tunnel erosion in a dam constructed from soils derived from Permian mudstone. This dam is known to have failed on first filling. The image was taken from the dam floor.

Source: Dispersive Soils and their Management Technical Reference Manual, Tasmania, 2009

Figure 2.2.3 Internal Erosion: Piping and Tunnel Formation

2.2.2.2 Surface Erosion, Subsidence (Dragon Holes), and Damage Cases

Damage associated with dispersive soils often includes surface erosion, subsurface tunnel erosion, and the formation of vertical or near-vertical voids, commonly referred to as “dragon holes.” In geotechnical literature, such features are sometimes described as “jugs” (i.e., narrow-necked earthen cavities, likened to water containers).

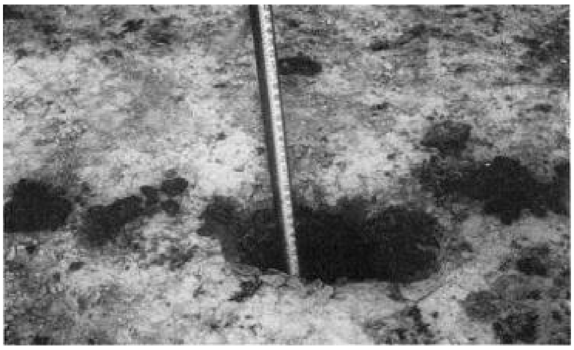
In Cambodia, these phenomena have been widely observed alongside roads and irrigation canals, where they are colloquially termed “dragon holes”. These cavities typically originate from minor surface irregularities, such as:

- Dry cracks in clayey soils
- Animal burrows or mole holes
- Decayed root channels
- Tracks left by vehicles or livestock
- Small surface depressions that accumulate rainwater and runoff

Once initiated, dragon holes may develop to depths of up to 3 meters, with bottom diameters of less than 1 meter. The initial surface opening is often small—frequently less than 25 mm—but expands as internal erosion progresses. Collapse commonly occurs when the internal void reaches a critical size or when the roof becomes structurally unstable due to loss of support.

In addition to vertical voids, slope surfaces may exhibit severe rilling (formation of small channels) or gully erosion. If unaddressed, these features can evolve into large sinkholes on roads, or cause seepage-induced failure in embankments and levees.

Notably, even when vegetation is well-established, dispersive soils often remain vulnerable to piping, gully formation, and other surface erosion mechanisms, as plant roots alone do not provide sufficient resistance to the intrinsic instability of the soil matrix.



Source: ENGINEERING ASPECTS OF SOIL EROSION, DISPERSIVE CLAYS AND LOESS, C.W. Lovel, Richard L. Wiltshire(1987)

Figure 2.2.4 Typical Piping Hole

Source: Study on the installation of drainage sheets with the functionality of eliminating rainwater infiltration that causes road cave-ins in Cambodia, JICA

Figure 2.2.5 *Surface Sinking Induced by Dragon Hole Formation*

Source: JICA Study Team

Figure 2.2.6 Damage at Tonle Sap Irrigation Project (Cambodia)

Source: Landslide Failure Mechanisms of Dispersive Soil Slopes in Seasonally Frozen Regions, Lixiang Wang, Xiaoming Yuan and Miao Wang, 2020

Figure 2.2.7 *Various Examples of Collapse in Dispersive Soils*

2.2.3 Responses During the Planning and Research Phase

> During the planning and site investigation stages, it is essential to determine whether dispersive soils are present at the proposed project site and to assess whether countermeasures are necessary. Dispersive soils are commonly found in areas underlain by parent rocks containing dispersive clay minerals or in saline and sodic soils with elevated Na^+ content.
>
> To delineate the distribution of dispersive soils, practitioners should refer to soil distribution maps and risk maps (such as those included in this handbook). These tools can support the identification of soil conditions at the target site, which should then be verified through appropriate surveys and laboratory testing.
>
> There are four primary test methods used to determine dispersivity:
>
> - Double hydrometer test
> - Crumb test
> - Pinhole test
> - Chemical analysis (e.g., ESP, SAR)
>
> No single method is conclusive on its own; therefore, it is recommended to apply multiple complementary tests to confirm results. However, due to constraints related to construction schedule, budget, and equipment, it may not be feasible to test every soil sample on site. At minimum, the double hydrometer and crumb tests should be performed, with the pinhole test and chemical analyses added where site conditions suggest elevated geotechnical risk.

［Explanation］

2.2.3.1 Distribution of Dispersive Soils

At present, there is no globally unified mapping of dispersive soil distribution. However, various sources report the occurrence of dispersive soils in the following regions:

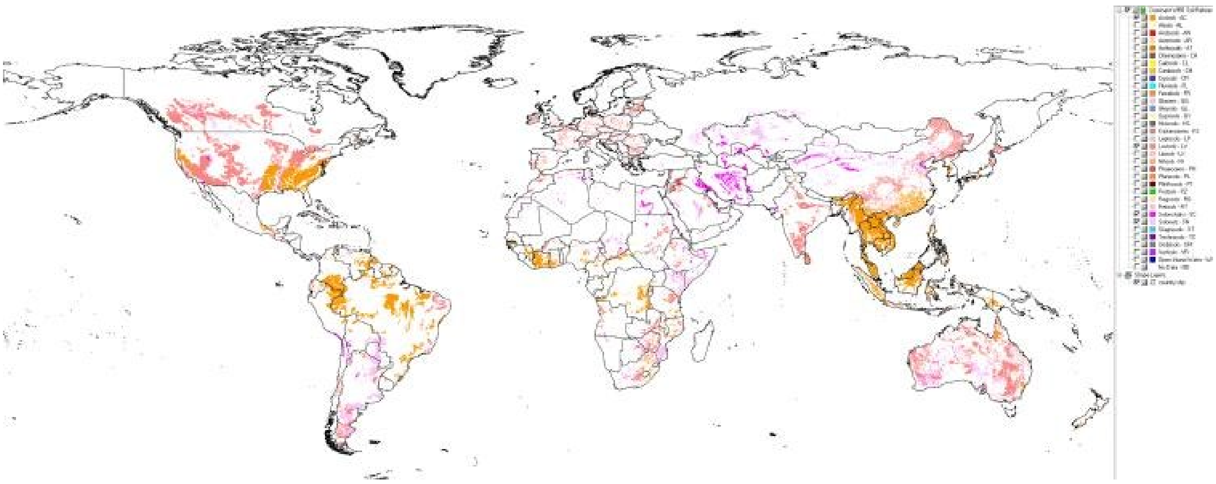
- Cambodia: Mekong River and Tonle Sap Lake basins, widespread alluvial wetlands
- Australia: Especially Tasmania and regions with sodic Vertisols
- Thailand: Northeastern region
- South Africa: Senekal Dam region
- United States: Great Lakes and prairie regions
- Greece, India (humid zones, river basins), Latin America,
- Indonesia: Java, Sumatra
- China: Yangtze and Yellow River basins
- Bangladesh: Ganges and Brahmaputra Delta
- Nigeria: Niger and Beni River basins
- Israel: Mediterranean coastal plain, Jordan River basin
- Iran, Spain, Ukraine (Black Sea–Chernobyl region), Brazil, New Zealand, Mexico, Vietnam

The soils most likely to become dispersive soils are listed in Table 2.2.1. Figure 2.2.8 shows the distribution of Solonetz, Solonchak and Acrisols, which are considered likely to be dispersive soils. In order to further verify whether the soil is dispersive or not, it is recommended to check the HWSD SMU table to see if the ESP (Exchangeable sodium percentage) value exceeds 15% to determine whether the soil is dispersive or not.

Table 2.2.1 Major Soil Classifications Estimated as Dispersive Soils
(Based on HWSD / FAO-UNESCO)

Soil Classification	Characteristic Features	Remarks
Solonetz	Sodic soils with high exchangeable Na^+	Highly dispersive
Solonchak	Saline soils	Na^+ leaching can induce dispersivity
Vertisols	Expansive clays	Dispersivity enhanced with high Na^+ (e.g., in Australia)
Acrisols / Luvisols / Alfisols	Tropical/humid region soils	Potentially dispersive; common in Cambodia and other countries

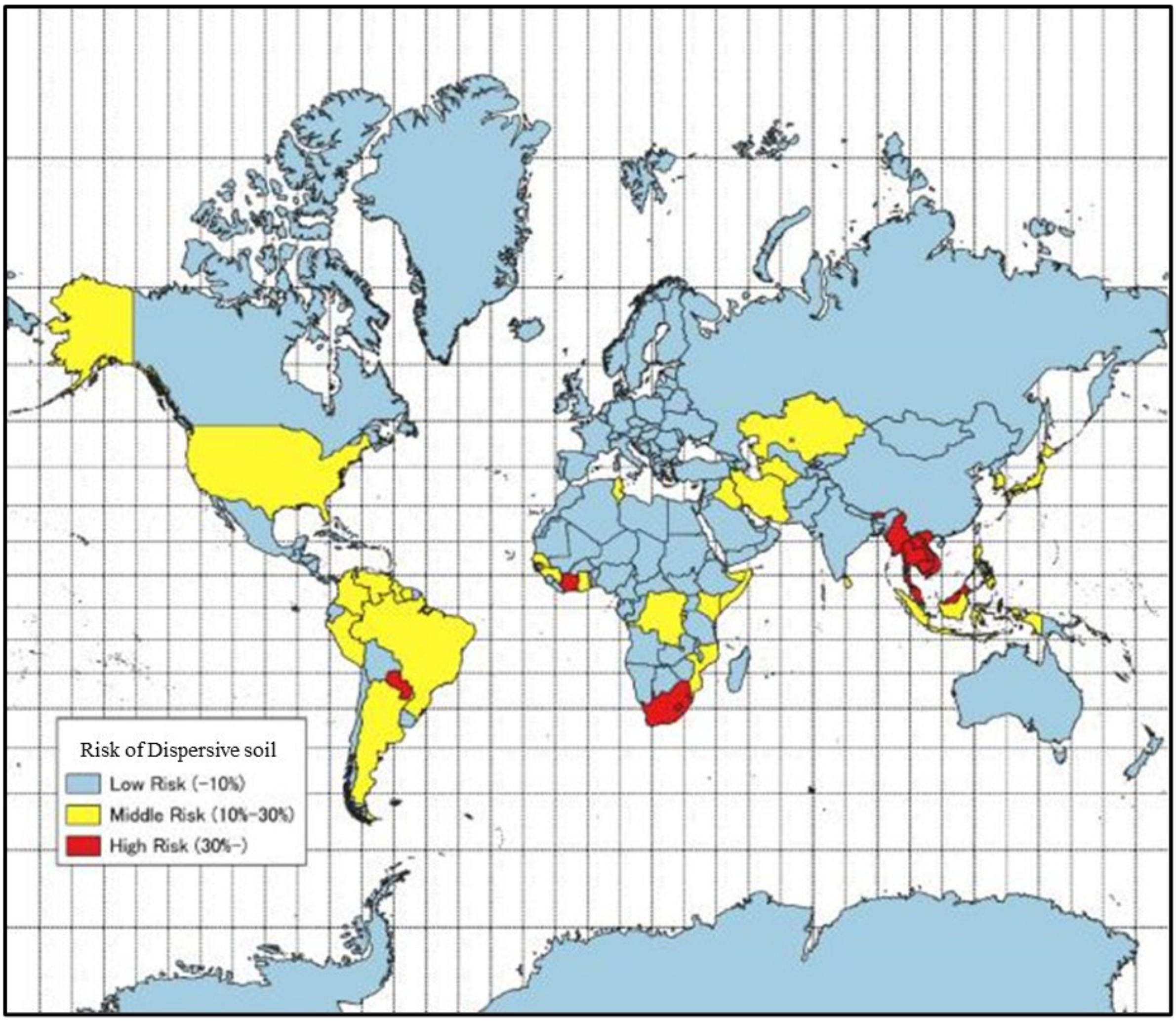
Source: *JICA Study Team*



Source: Prepared by JICA Study Team using HWSD Ver. 2.0

Figure 2.2.8 Global Distribution of Solonetz, Solonchak, and Acrisols

Based on the distribution map shown in Figure 2.2.8 and other data, the percentage of area distributed in each country is calculated, and the percentage of area in each country is calculated and illustrated as the degree of risk, as shown in Figure 2.2.9. If a project is to be implemented in a country that is considered to be at risk, referring also to this figure, it is necessary to conduct a thorough investigation regarding the presence or absence of dispersive soil.



Source: JICA Study Team

Figure 2.2.9 Distribution risk of dispersive soils

2.2.3.2 Dispersive Soil Determination Method

The identification of **d**ispersive clays relies on a suite of four primary test methods. To ensure reliable results, test specimens must be collected and preserved at their natural moisture content and should be sealed in moisture-tight containers during transport and storage. Since no single test provides definitive classification, a combination of multiple test methods is strongly recommended.

1. Recommended Test Sequence:
2. Pinhole Test
3. Double Hydrometer Test
4. Chemical Analysis
5. Crumb Test

As a minimum, the double hydrometer test and the crumb test should be conducted. If resources allow, chemical analysis should also be performed to supplement these results.

Table 2.2.2 Test Methods to Determine Dispersibility

Test Name	ASTM Standard	Characteristics and Positioning
Pinhole Test	ASTM D4647 Standard Test Method for Identification and Classification of Dispersive Clay Soils by the Pinhole Test	Most reliable test method; simulates physical piping behavior. Recommended for critical structure design (e.g., embankment dams). Requires specialized equipment.
Double Hydrometer	ASTM D4221 Standard Test Method for Dispersive Characteristics of Clay Soil by Double Hydrometer	Quantitative test that calculates Dispersion Ratio (DR). Practical, relatively simple, and useful for supplementing or replacing the pinhole test.
Crumb Test	ASTM D6572 Standard Test Methods for Determining Dispersive Characteristics of Clayey Soils by the Crumb Test	Simple and rapid visual classification test. Useful for preliminary screening, though not highly accurate.
Chemical Analysis	ASTM D6919 Standard Test Method for Determination of Dissolved Alkali and Alkaline Earth Cations in Water by Ion Chromatography	Laboratory-based method using ion chromatography to evaluate ESP, SAR, and other relevant chemical indices. Highly accurate but less common in civil practice.

***Source**: JICA Study Team*

(1) Crumb Test Evaluation

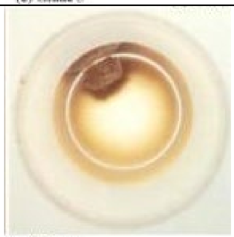
The crumb test is a rapid field or laboratory test used for initial identification of dispersive clay behavior. Originally developed by Emerson (1967) and later simplified by Sherard (1976), it employs a four-tier rating system based on visual assessment of dispersion.

Procedure:

- Prepare a cube-shaped soil sample approximately 16 mm × 6.5 mm.
- Place the sample in distilled water and observe for signs of dispersion.
- For disturbed soils, sieve to ≤ 0.425 mm, remold, and compact into test cubes.
- The same preparation method applies when the sample is also to be used in the pinhole test.

Important Note:
The crumb test is sensitive to the presence of dispersive behavior but not definitive for its absence. A non-dispersive result does not guarantee stability, and thus the test should only be used as a preliminary screening tool. It is strongly recommended to combine the crumb test with the double hydrometer and/or pinhole tests for reliable classification.

Table 2.2.3 Dispersivity Classification by Crumb Test

Dispersivity Classification	Observed Dispersion Behavior	Degree of Dispersion	ASTM Dispersivity Description
Non-Dispersive	 (a) Grade 1	Clod remains stable; water remains clear	The soil may disintegrate, settle, diffuse, and spread, but no cloudiness caused by colloidal suspension is observed. All particles settle within the first hour.
Low Dispersive	 (b) Grade 2	Clod disintegrates slowly; water becomes slightly turbid	Grade 2 represents a transitional grade. A faint, barely visible colloidal suspension causes minor turbidity near the soil particle surface. If a visible cloud is easily observed, assign Grade 3. If only a faint cloud is visible in a small localized area, assign Grade 1.
Moderately Dispersive	 (c) Grade 3	Clod disintegrates relatively quickly; water becomes moderately turbid	A cloud of suspended clay colloids can be readily observed extending beyond the soil particle surface. The cloud may extend up to 10 mm from the clod along the bottom of the container.
Highly Dispersive	 (d) Grade 4  (e) Grade 4	Clod disintegrates rapidly; water becomes highly turbid	Dense and abundant clouds of clay colloids are visible throughout the bottom of the container. In some cases, dispersion is so extensive that it is difficult to distinguish the original clod from the colloidal suspension. The suspension is often clearly visible along the sides of the container.

Source: JICA study team

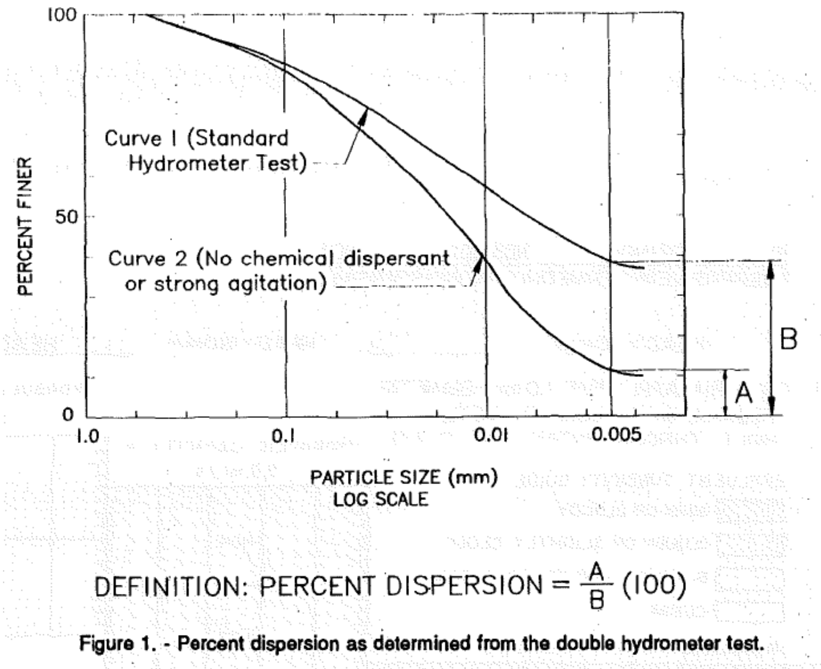
(2) Determination by Double Hydrometer Test

The double hydrometer test is a quantitative laboratory method used to evaluate the dispersibility of clay soils. The procedure involves performing two hydrometer analyses: one with a chemical dispersant (typically sodium hexametaphosphate) and one without. By comparing the percentage of particles finer than 0.005 mm (5 μm) in both tests, the Dispersion Ratio (DR) is calculated.

Formula for Dispersion Ratio:

$$\text{Dispersion Ratio (\%)} = \frac{\textbf{Percent passing 5 μm without dispersant}}{\textbf{Percent passing 5 μm with dispersant}} \times 100$$

This ratio reflects the degree to which the soil naturally disperses in water, which is a key indicator of its erosion susceptibility.



***Source**: Characteristics and Problems of Dispersive Clay Soils, Paul C. Knode, U.S. Bureau of Reclamation, 1991*

Figure 2.2.10 Procedure for Determining Dispersion Ratio Using the Double Hydrometer Test

The classification of soil dispersibility based on the Dispersion Ratio varies slightly among researchers. The following criteria, adopted from Elges (1985) and supported by field experience, are commonly referenced:

While the double hydrometer test demonstrates an approximate 85% accuracy in predicting dispersive behavior (i.e., 85% of soils with DR > 35% show field evidence of dispersion), false negatives may occur. Hence, this method should be used in conjunction with:

- Crumb test
- Pinhole test
- Chemical analysis of pore water (e.g., ESP, SAR)

Table 2.2.4 Dispersibility Classification by Dispersion Ratio

Dispersion Ratio (DR %)	Interpretation
< 15%	Non-dispersive
15–30%	Slightly dispersive
30–50%	Moderately dispersive
> 50%	Highly dispersive

Source: JICA Study Team

(3) Determination by Chemical Analysis

Chemical analysis is an effective supplementary method for identifying dispersive soils, primarily through the assessment of cation balance and soil salinity (electrical conductivity, EC). However, since the chemical behavior of expansive soils and dispersive soils overlaps significantly, chemical indices should not be used in isolation for definitive classification.

1) Evaluation by ESP (Exchangeable Sodium Percentage)

The ESP value quantifies the proportion of exchangeable sodium ions (Na^{+}) relative to the soil's cation exchange capacity (CEC). Elevated ESP values are associated with:

- Disruption of particle cohesion,
- Swelling of clay minerals,
- Increased risk of dispersion and internal erosion.

$$ESP = \frac{\text{Exchangeable Na}^{+}}{\text{CEC}} \times 100$$

Where:

- Exchangeable Na^{+} (meq/100g soil): Amount of sodium ions adsorbed on soil particle surfaces.
- CEC (meq/100g soil): Total capacity of the soil to hold cations (Na^{+}, Ca^{2+}, Mg^{2+}, K^{+}, etc.).

Although ESP is a strong predictor of dispersive potential, it should be used in conjunction with other tests, such as:

- pH and EC (electrical conductivity) measurements
- Double hydrometer or pinhole tests

Table 2.2.5 Dispersivity Evaluation Criteria Based on ESP

ESP (%)	Classification	Characteristics
<5	Non-Dispersive Soil	Stable interparticle bonding; low risk of erosion and dispersion.
5–15	Partially Dispersive Soil	Some parts of the soil may disperse. Dispersion may progress depending on flow velocity or water chemistry.
15–25	Dispersive Soil	Weak interparticle bonding; clear evidence of dispersivity.
25–40	Highly Dispersive Soil	High dispersivity with increased risk of piping and erosion.
>40	Extremely Dispersive Soil	Fully dispersive soil; potential for severe erosion. Typically classified as sodic soil.

Source: JICA Study Team

Table 2.2.6 Soil Classification Based on ESP

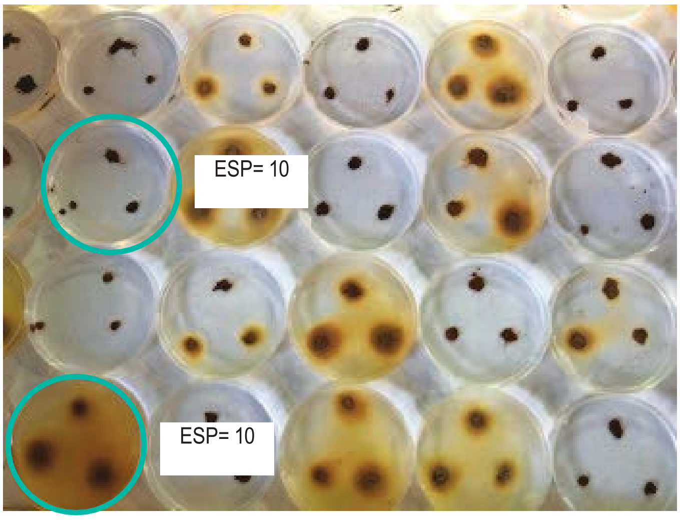
ESP (%)	Soil Classification	Characteristics
<15%	Non-Saline Soil	Low sodium concentration; no significant impact on crop growth.
15–40%	Alkali Soil	High sodium concentration reduces soil permeability; may negatively affect crop productivity.
>40%	Sodic Soil	Very high sodium concentration leads to soil structure collapse, reduced drainage, and loss of soil fertility; special reclamation measures are required.

Source: JICA Study Team

In Australian soil classification, an ESP > 5–6 is typically defined as sodic, and ESP > 15 as strongly sodic. While sodic soils are frequently dispersive, not all sodic soils exhibit dispersive behavior, and vice versa. There is no universal ESP threshold at which dispersibility occurs.

Observed Variability:

- 38% of soils with ESP > 5 did not exhibit dispersion
- Soils with ESP = 26 showed no dispersion in some cases
- 17% of soils with ESP < 6 showed dispersive behavior
- Even with ESP = 1–2%, dispersibility has been observed in distilled water



Source: Dispersive Soil Manual: Managing Dispersive Soils – Practicalities and Economics (Northern Region), David McKenzie & Alisa Bryce, 2023

Figure 2.2.11 Example of Dispersive and Non-Dispersive Behavior at ESP = 10 (Northern Australia)

2) Determination by ESI (Electrochemical Stability Index)

The Electrochemical Stability Index (ESI) is a quantitative parameter used to evaluate the chemical and physical stability of soils. It integrates two key variables:

- Electrical Conductivity ($EC_{1:5}$), a proxy for soil salinity, and
- Exchangeable Sodium Percentage (ESP), a measure of sodium-induced dispersion potential.

By combining these, ESI provides a refined index for assessing the risk of dispersion, swelling, and permeability reduction in fine-grained soils.

$$ESI = \frac{EC_{1.5}(\frac{dS}{m})}{ESP(\%)}$$

Where,

EC1.5: Electrical conductivity of a solution of soil and water mixed in a ratio of 1:5 (unit: dS/m)

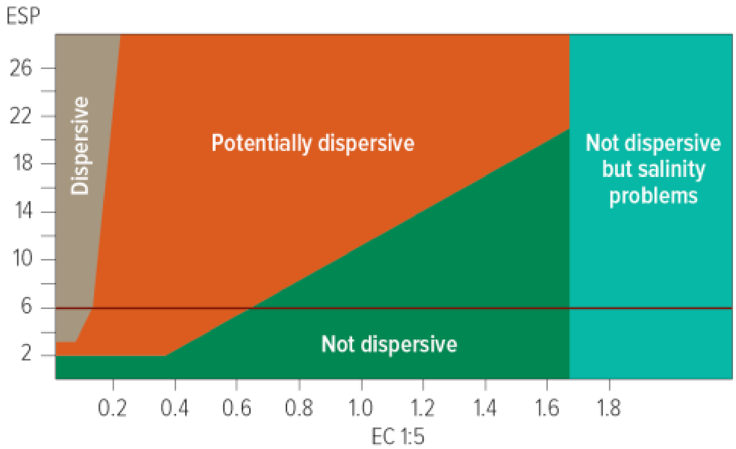
Table 2.2.7 Dispersivity Evaluation Criteria Based on ESI

ESI	Classification	Characteristics and Effects
> 0.1	Stable Soil	Soil particles are stable and have good permeability and structure.
0.05–0.1	Moderately Stable	Slight dispersion and reduced permeability may occur.
< 0.05	Unstable Soil	The soil is prone to dispersion, and there is a high risk of a significant decrease in permeability and swelling.

Source: JICA Study Team

ESI below 0.05 suggests that the soil is dispersive, and below 0.02 often indicates strong dispersibility; ESI is said to be a more effective indicator for determining dispersibility than ESP; Central West CMA (2008) and Hazelton and Murphy (2016) use the relationship diagram between salinity EC1.5 and ESP shown in Figure 2.2.12

The relationship diagram between salinity EC1.5 and ESP, shown in Figure 2.2.12, is used to determine dispersibility. This approach enables more granular assessment of dispersive potential.



Source: Adapted from Central West CMA (2008), and Hazelton and Murphy (2016).
A more detailed version is shown in Appendix D.

Source: Dispersive Soil Manual: Managing Dispersive Soils – Practicalities and Economics (Northern Region), David McKenzie & Alisa Bryce (2023); ESI-based analysis and classification adapted by JICA Research Team.

Figure 2.2.12 Salinity–Sodicity Relationship Chart ($EC_{1:5}$ vs. ESP)

3) Determination by SAR (Sodium Adsorption Ratio)

The Sodium Adsorption Ratio (SAR) is an index used to assess the relative concentration of sodium ions (Na^{+}) in soil pore water compared to calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions. While Ca^{2+} and Mg^{2+} contribute to the cohesion and flocculation of soil particles, high sodium concentrations weaken inter-particle bonding, increasing the potential for dispersion, erosion, and structural collapse of clayey soils.

$$AR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}}$$

Where:

- **Na^{+}**: Sodium concentration (meq/L, milliequivalents per liter)
- **Ca^{2+}**: Calcium concentration (meq/L)
- **Mg^{2+}**: Magnesium concentration (meq/L)

The criteria for determining dispersibility by SAR values are shown in Table 2.2.8.
If SAR > 13, the risk of dispersibility is high and careful design and study on countermeasures are required. This indicator is widely used as an initial diagnosis of soil because it can be ascertained even by simple analysis. However, since there is a limit to the ability to determine the SAR alone, a multifaceted evaluation in combination with ESP, EC, ESI, etc. is desirable.

Table 2.2.8 Dispersivity Evaluation Criteria Based on SAR

SAR	Dispersivity Evaluation	Characteristics
<6	Non-Dispersive	Soil structure remains stable; low risk of dispersion or erosion.
6–12(13)	Low Dispersivity	Partial dispersion may occur; under certain conditions, structural instability may develop.
12(13)–20	Moderately Dispersive	Dispersivity increases; soil particles tend to separate in water, increasing erosion risk.
>20	Highly Dispersive	Soil structure becomes highly unstable; piping and erosion are likely. Reinforcement measures are necessary.

Source: JICA Study Team

4) Determination by CROSS (Cation Ratio of Soil Structural Stability)

Although ESP (exchangeable sodium percentage) and SAR (sodium adsorption ratio) have been widely used to evaluate soil dispersibility, these indicators have the following limitations.

- Potassium (K^{+}) is neglected in ESP and SAR.

- Calcium (Ca^{2+}) and magnesium (Mg^{2+}) are considered equally effective in SAR, but in reality there are differences in cohesion.

The Cation Ratio of Soil Structural Stability (CROSS) was proposed by Rengasamy & Marchuk (2016) to more accurately reflect such real-world soil chemistry.

CROSS is calculated by considering the relative cohesion of the major cations as follows: Mg^{2+} is considered more cohesive between particles than Ca^{2+}, and K^{+} also has slightly higher cohesion than Na^{+}.

$$CROSS = \frac{Na + 0.56K}{\sqrt{Ca + 0.6Mg}}$$

Where:

Na^{+}: Sodium ion concentration (meq/L)
K^{+}: Potassium ion concentration (meq/L)
Ca^{2+}: Calcium ion concentration (meq/L)
Mg^{2+}: Magnesium ion concentration (meq/L)

The criteria using CROSS are shown in Table 2.2.9.
CROSS is the only chemical indicator that can take into account the influence of K^+ and is more faithful to actual soil behavior by reflecting the difference in cohesion between Mg^{2+} and Ca^{2+}. Unlike ESP and SAR, it can evaluate the "quality" of chemical structural stability. Therefore, it can be used in combination with EC, ESP, SAR, ESI, etc., rather than alone in the evaluation of dispersive soils to provide a reliable diagnosis.

Table 2.2.9 Dispersivity Evaluation Criteria Based on CROSS

CROSS	Dispersivity Classification	Characteristics and Implications
>10	Stable Soil	Soil structure is highly stable with negligible risk of dispersion.
5–10	Moderately Stable Soil	Some risk of dispersion under certain conditions; generally stable under normal conditions.
2–5	Dispersive Soil	Soil tends to begin dispersing; risk of aggregate breakdown increases.
<2	Highly Dispersive Soil	Soil particles disperse readily, leading to significant loss of permeability and structural integrity.

Source: JICA Study Team

5) Determination of Dispersion by Diagram

Methods have been developed to visually determine the chemical properties of dispersible soils using not only mathematical formulas but also diagrams. In particular, graphical diagrams of the relationship between sodium percentage (Na^+) and cation exchange capacity (CEC) are useful for determining dispersibility trends.

Figure 2.2.13 shows a dispersibility determination chart based on total dissolved salt (TDS) and Na+/TDS.

$$Percent\ Solution\ (\%) = \frac{Na^+}{Ca^{2+} + Mg^{2+} + Na^+ + K^+} \times 100 = \frac{Na^+}{TDS} \times 100$$

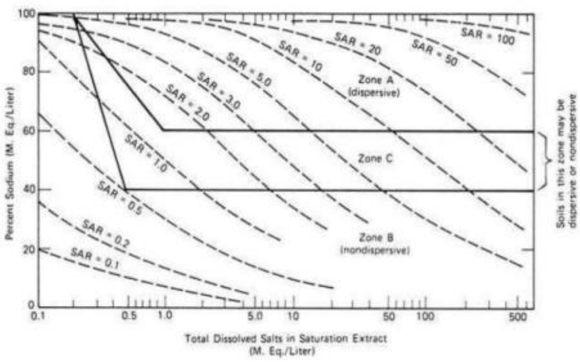
The concept of judgment is shown below.

- High Na^+/TDS, low TDS → high dispersibility

- Na^+/TDS is low and TDS is high → Stable soil

- A threshold line is drawn on the graph, and judgments are classified as “stable,” “unstable,” or “transition zone” based on that line.

Figure 4: Determination of dispersive soil in Chemical test



***Source**: A State of the Art Review of Dispersive Soils: Identification Methods Perspective, Shoghi et al. (2013)*

Figure 2.2.13 Dispersibility Classification Based on TDS vs Na^+/TDS

Figure 2.1.14 visually illustrates that soil dispersibility is determined by the "combination" of CEC and ESP. The decision areas are usually classified as follows:

- High ESP + Low CEC → Highly Dispersive
- Low ESP + High CEC → Stable
- Intermediate values → Transitional Zone

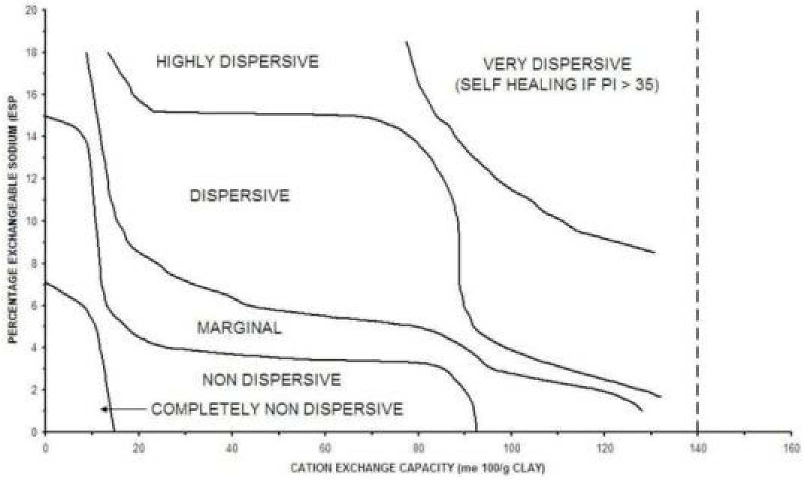


Figure 2-8: Diagram of determination of dispersion potential as a function of ESP and CEC (Gerber and Harmse, 1987)

***Source**: Evaluation of Test Protocols for Dispersive Soil Identification in Southern Africa, Amrita Maharaj (2023)*

Figure 2.2.14 Dispersibility Assessment Chart Based on CEC vs ESP

Another proposed method is to use the flow shown in Figure 2.2.15 to make a determination. This is a diagnostic process that is adapted to the field, where the initial stage of judgment is narrowed down by chemical indicators, and the final judgment is supported by physical tests.

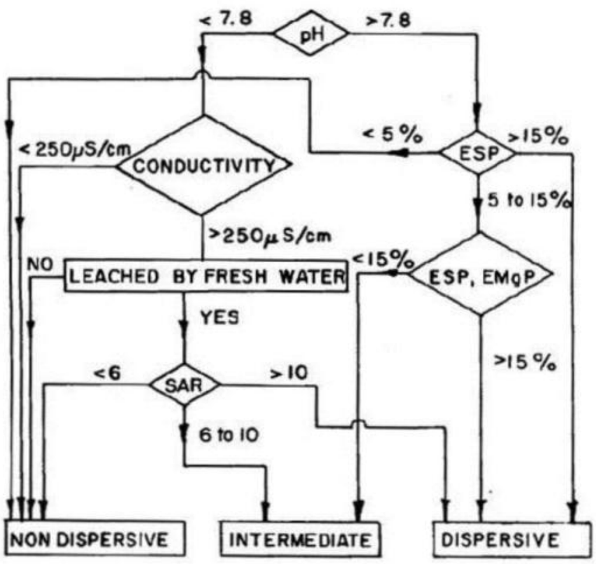


Figure 2-9: Alternative procedure for identification of dispersive soils. (Gerber and Harmse, 1987)

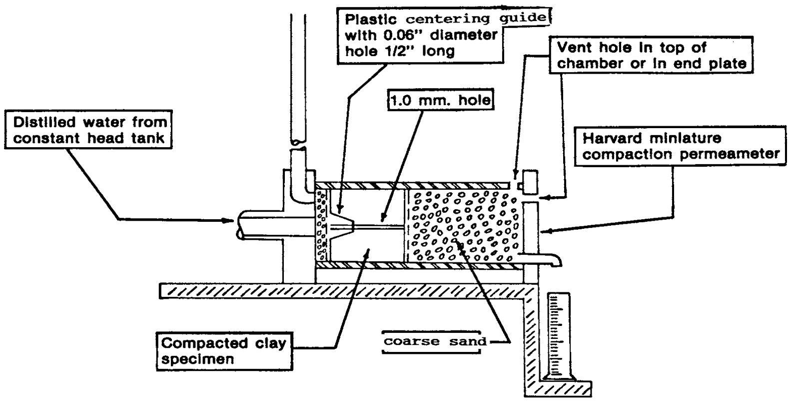
Source: Evaluation of Test Protocols for Dispersive Soil Identification in Southern Africa, Amrita Maharaj (2023)

Figure 2.2.15 Diagnostic Flowchart for Dispersive Soil Classification

(4) Determination of Dispersibility by Pinhole Test

The pinhole test is a direct physical test used to identify dispersive cohesive soils. It was developed to evaluate the colloidal erodibility (piping) of cohesive soils used in structures such as levees, channels, and earth dams. The test method and evaluation criteria have been established based on the results of hundreds of tests conducted by Sherard et al. on clay soils of structures that have actually undergone/endured erosion in nature.

The pinhole test specimens are 30-38 mm in diameter and 38 mm in length. The diameter is not specified, but is adapted to the test apparatus. The pinhole test specimens are made in 5 lifts, tightening 16 times per lift using a 6.8 kg spring-loaded tamper. Its density will be approximately 95% of the maximum dry unit weight. Since the test results are not affected by the dry unit weight, it is not necessary to set a strict density. A 1 mm hole is drilled in the specimen and distilled water is passed through the hole at 50 mm, 180 mm, 380 mm and 1020 mm waterhead. Dispersibility is classified based on the turbidity of the effluent, final hole diameter, and flow rate.



Source: ASTM D4647

Figure 2.2.16 Schematic Diagram of Pinhole Test Apparatus

The test procedures are the same for Method A, Method B, and Method C, with different criteria to determine (Table 2.1.10, Table 2.1.11, Table 2.1.12). Methods A and C measure the turbidity of the runoff, the final size of the pinhole, and the flow rate through the pinhole to classify soil dispersion characteristics, while Method B does not measure flow rate.

Operational considerations for determination are listed below.

- ND2: Projects not related to public safety are likely not to be a problem without additional measures

- ND3, SD: High uncertainty, verification with additional samples is desirable

- D1, D2, D: Highly dispersive, requiring measures such as filters, cement/lime stabilization treatment, etc.

Table 2.2.10 Dispersivity Classification by Method A

Classification	Degree of Dispersivity	Evaluation Method
D1, D2	Dispersive	Rapid failure under a 50 mm head.
ND4, ND3	Slight to Moderate	Slow erosion under 50 mm or 180 mm head.
ND2, ND1	Non-Dispersive	Very little or no colloidal erosion under 380 mm or 1020 mm head.

Source: JICA Study Team

Table 2.2.11 Dispersivity Classification by Method B

Classification	Degree of Dispersivity	Evaluation Method
D	Dispersive	Rapid erosion under a 50 mm head.
SD	Slightly Dispersive	Slow erosion under a 180 mm head.
ND	Non-Dispersive	Very little or no colloidal erosion under a 380 mm head.

Note 2: In Method B, dispersivity categories are grouped as follows: D = D1, D2, ND4; SD = ND3; and ND = ND2, ND1.

Source: JICA Study Team

Table 2.2.12 Dispersivity Classification by Method C

Classification	Degree of Dispersivity	Evaluation Method
D1, D2	Dispersive	Rapid failure under a 50 mm head.
ND4, ND3	Slight to Moderate	Slow erosion under a 50 mm, 180 mm, or 380 mm head.
ND2, ND1	Non-Dispersive	Very little or no colloidal erosion under a 380 mm head.

Source: JICA Study Team

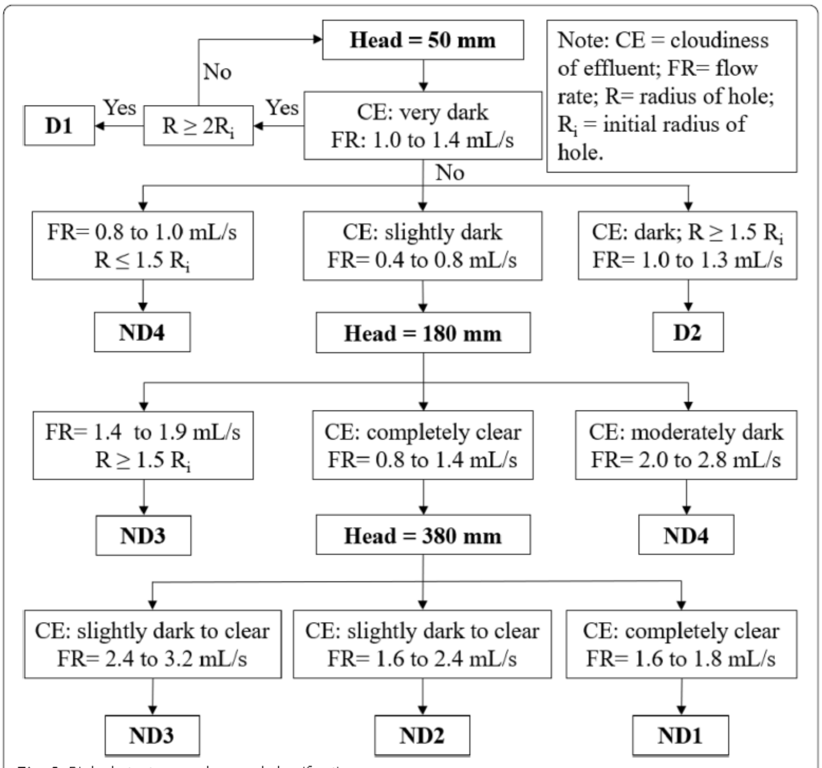
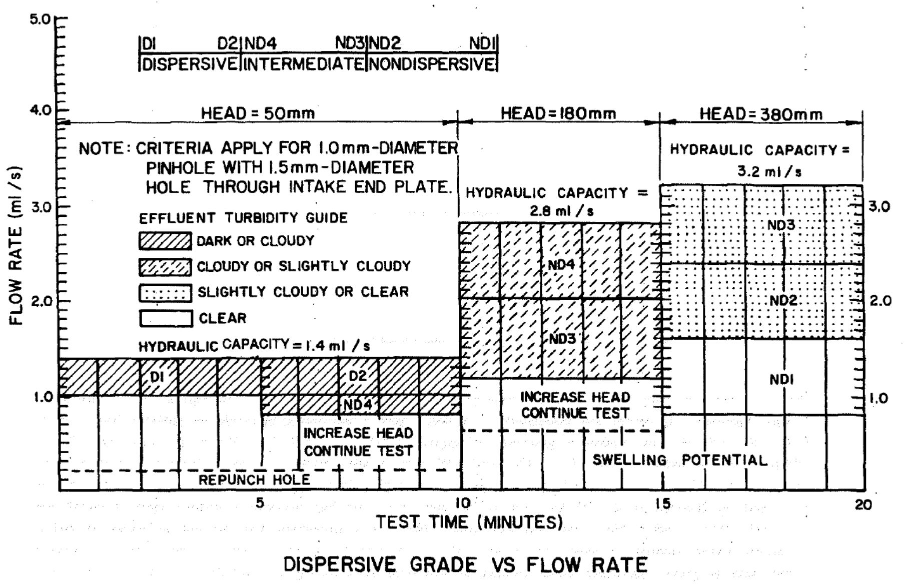


Fig. 8 Pinhole test procedure and classification

Source: Evaluation of erosion characteristics of soils using the pinhole test, Ba Huu Dinh, Anh-Dan Nguyen, Seo-Yong Jang, Young -Sang Kim(2021)

Figure 2.2.17 Interpretation Method for Pinhole Test Results



Source: CHARACTERISTICS AND PROBLEMS OF DISPERSIVE CLAY SOILS, Paul C. Knode, U.S. DEPARTMENT OF THE INTERIOR Bureau of Reclamation, 1991

Figure 2.2.18 Pinhole test determination method

2.2.4 Measures to Be Taken at the Design and Construction Stage

If it is determined during the planning and investigation phase that dispersive soils will be distributed, measures to minimize the risk of dispersive soils that may occur during and after construction should be considered. The risk of dispersive soil, if it occurs, may be accompanied by extensive damage, such as widespread erosion, cave-ins, and collapses. Therefore, in order to develop a safe and rational project plan, it is necessary to take into consideration the risks assumed from the basic planning and design stages, such as road alignment and structure layout, at the design stage.

Since most of the damage caused by dispersive soils is caused by water supply from slopes and cracks, sufficient attention should be paid to drainage of the targeted structures and protection from water intrusion. Countermeasure works include the installation of appropriate filter materials, slope protection with concrete, etc., and the installation of impervious sheets. Chemical stabilization can also be used to control the dispersibility of dispersible soil.

In the design stage, specific values for the type and thickness of filter materials and protection works, the type and mixing ratio of improvement materials, water content ratio, degree of compaction, etc., should be considered and set according to the selected countermeasure works, the scope of application of the countermeasure should be clearly indicated on the drawings, and construction specifications and quality control standards should be considered and set.

At the construction stage, based on the design drawings and specifications, sufficient care should be taken to minimize risk in consideration of the purpose of the countermeasure construction while conducting quality control in accordance with the specifications. In addition, since dispersive soils vary widely in characteristics from region to region, and there is a possibility that the expected sufficient countermeasure effect may not be achieved, it is desirable to incorporate test construction into the project if the risk is high.

[Explanation]

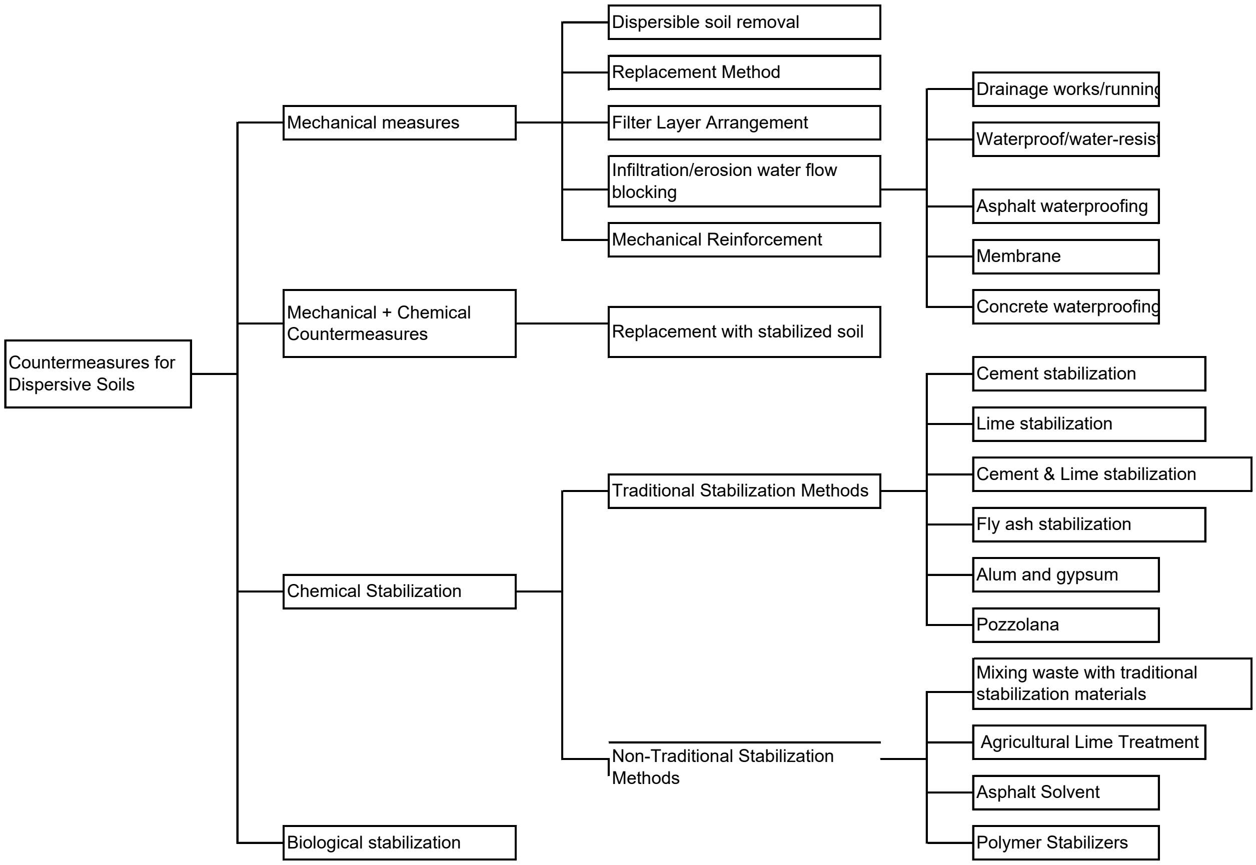
2.2.4.1 Considerations for the Design and Selection of Countermeasure Works

In the selection and design of countermeasure works for dispersive soils, the following factors must be evaluated:

- Scale of the project
- Construction financing phases (e.g., initial investment for pond reclamation or treatment)
- Nature and functional requirements of the facility (e.g., airport runway vs. local road)
- Cost-effectiveness relative to alternative construction methods

Currently, there is a lack of comprehensive design manuals or textbooks specifically addressing countermeasures for dispersive soils. As a result, mitigation techniques are developed by drawing on multidisciplinary knowledge, practical case studies, and engineering judgment.

A summary of potential countermeasures for dispersive soils based on field experience is provided in Figure 2.2.19.



***Source**: JICA Study Team*

Figure 2.2.19 Typical Countermeasure Methods for Dispersive Soils

Table 2.2.13 Major Countermeasure Methods Applicable to Dispersive Soils

Stabilization Method	Overview of Treatment Method	Advantages	Disadvantages
Removal and Replacement Method	Remove dispersive soil and replace it with non-dispersive soil.	Simple and easy to implement. In many cases, faster than other methods. Considered the most reliable and effective countermeasure.	May not be practical depending on the required extent and thickness. Risk of damage during construction due to water infiltration during excavation. Difficult to apply in areas where securing high-quality replacement material is challenging.
Placement of Filter Layers	Install sand filters to block and control seepage through dispersive clays.	Easy to construct. Sand filters can prevent silt-sized particles from migrating with water flow.	Cannot completely prevent the passage of suspended colloidal clay particles. To effectively seal cracks, non-cohesive materials are required.
Blocking of Seepage/Erosion Water Paths	Cover the surface and sides of dispersive soil embankments with various materials or structures to prevent infiltration and suppress the formation of desiccation cracks.	Simple construction method. Effectively prevents the infiltration of water, a major deterioration factor.	Drying of materials or slopes before protection installation may lead to desiccation cracks. Some materials (e.g., concrete block structures) can result in higher construction costs.
Mechanical Reinforcement	Improve reconstituted soils in pavement subgrades, etc., by adding fibrillated polypropylene fibers, CBR fiber reinforcement, natural fibers, glass fibers, etc.	Can improve inter-particle shear strength. Stabilization through increased cohesion is expected. Possible use of locally available natural fibers.	Challenges in achieving uniform mixing of fibers on-site. More effective in coarse-grained soils; limited effectiveness when used alone in clay soils. Effective when combined with chemical stabilization.
Chemical Stabilization	Improve the physicochemical properties of dispersive soils through chemical reactions and cation exchange.	Economically advantageous in areas where replacement material is scarce. Dispersive soils can be completely converted into non-dispersive soils by adding chemical stabilizers such as hydrated lime (calcium hydroxide), gypsum (calcium sulfate), alum (aluminum sulfate), fly ash, agricultural lime, magnesium chloride, combinations of hydrated lime and agricultural lime, molasses, asphalt emulsions, or polymers.	Quality may deteriorate if stabilizers contain many impurities. Difficulty in obtaining stabilizers. Increased competition for stabilizers from industrial sectors and substantial reductions in government subsidies for environmental use, leading to cost increases.

Source: JICA Study Team

In regions where securing replacement materials is difficult, chemical stabilization is considered a more economically viable countermeasure. The main chemical stabilizers and their characteristics for use in chemical stabilization are summarized in Table 2.2.14 .

Table 2.2.14 Major Chemical Stabilizers and Their Characteristics

Stabilizer	Main Component	Effects and Characteristics	Considerations
Hydrated Lime ($Ca(OH)_2$)	Source of Ca^{2+}	Highly effective in suppressing dispersivity and swelling. Inexpensive and widely used.	Reaction inhibited by high organic content. Attention needed for dust generation during construction.
Gypsum ($CaSO_4$)	High electrolytes + Ca^{2+}	Effective in initial strengthening of electrolyte concentration. Particularly effective in arid regions.	Low solubility and relatively high cost.
Alum ($Al_2(SO_4)_3$)	Source of Al^{3+}	Rapid flocculation of clay particles.	Potential risk of excessive acidification in some soils.
Agricultural Lime (Calcium Carbonate)	Mild source of Ca^{2+}	Inexpensive and environmentally friendly.	Effect develops slowly.
Fly Ash (By-product of Thermal Power Plants)	SiO_2, Al_2O_3	Stabilizes through pozzolanic reaction when combined with lime.	Insufficient when used alone.
Ground Granulated Blast Furnace Slag (GGBS)	CaO, SiO_2, etc.	Enhances strength when combined with cement or lime.	Inexpensive as an industrial by-product. Contributes to long-term strength development.
Polymers (Synthetic/Natural)	Molecular binders	Effective for dispersivity containment and workability.	Further verification needed for durability and cost performance.
Asphalt Emulsions, Molasses	Organic-based materials	Provide water-proofing and moisture retention through surface coating.	Attention required for odor and volatility. Limited field application experience.

Source: JICA Study Team

Chemical stabilization is an effective technique for mitigating the dispersive behavior of dispersive soils while improving their engineering properties, such as strength, stiffness, and permeability. However, the following limitations and precautions should be carefully considered during design and material selection:

1. Adverse Effects in the Presence of Sulfate Ions

When sulfate ions (SO_4^{2-}) are present in dispersive soils, lime stabilization treatment may result in the formation of a swellable layer. This is because Ca^{2+} (the main component of lime) reacts with SO_4^{2-} to form gypsum ($CaSO_4$-$2H_2O$), which causes crystal swelling. As a result, the strength of the soil may be adversely affected. The sulfate content of the soil should be checked in advance, and sulfate-resistant stabilizing materials (e.g., sulfate-resistant cement) should be considered if necessary.

2. Limitations of Using Portland Cement Alone

Cement is effective for normal swelling clays, but is not necessarily superior to lime for dispersible clays. Although stabilization with cement is effective in improving initial strength, it is often insufficient to control dispersibility (chemical stability). Replacement of sodium ions is important for dispersion control, and lime (Ca^{2+} source) is more likely to act directly. If dispersion control is the primary objective, consider using lime or gypsum in combination with lime or gypsum, or with other pozzolanic reactants.

3. Dispersion Resistance ≠ Mechanical Strength

Stabilized soils that are most resistant to dispersion and erosion are not necessarily resistant to mechanical stresses such as physical loading and cracking. For example, brittle fracture may occur even with high strength, or performance may deteriorate due to cyclic loading or dry/wet cycling. A composite treatment is needed to achieve both dispersion control and mechanical resistance (e.g., lime + fiber reinforcement, gypsum + cement, etc.).

2.2.4.2 Related Standards for Countermeasure Construction

Currently, there are no formal international or unified design standards specifically addressing dispersive soils. Furthermore, countermeasures are generally developed based on local conditions, site-specific risk assessments, and empirical experience. However, in countries such as Australia, where the engineering community has placed significant emphasis on the challenges posed by dispersive soils, regional guidelines and technical references have been published and are widely regarded as practical and instructive.

- Dispersive Soils and Their Management: Technical Reference Manual, Tasmania (2009)
- Implementation Guideline No. 28: Ipswich Planning Scheme (2016)

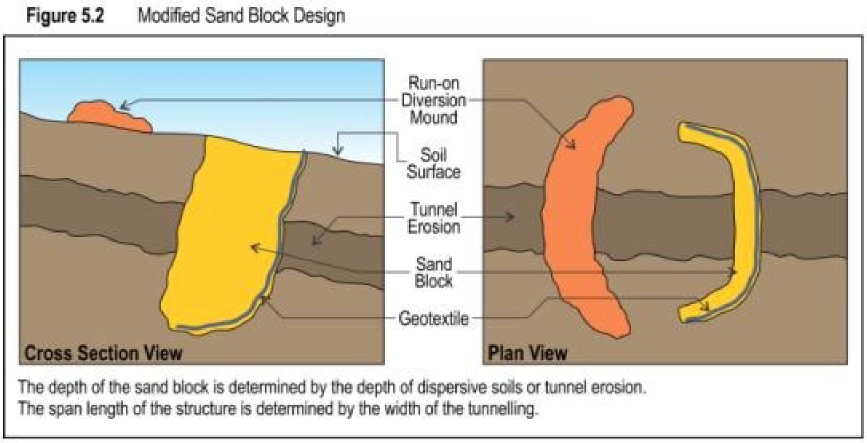
Guidelines for the Management of Dispersive Soils in the City of Ipswich (2016)

1) Objective:

To provide a framework incorporating both engineering and environmental measures that aim to prevent, mitigate, and manage erosion and structural degradation caused by dispersive soils.

2) Dispersive Soil Management:

1. Identification and Avoidance of Dispersive Soils
   Early detection through geotechnical surveys and diagnostic tests (e.g., pinhole test, crumb test) to identify high-risk zones.
2. Soil Re-compaction
   Re-compacting cut or fill areas post-grading to reduce soil permeability and minimize water infiltration.
3. Chemical Modification
   Application of chemical stabilizers, primarily gypsum ($CaSO_4$), to replace exchangeable Na^+ and improve soil structure.
   Note: Monitor for pH shifts and impact on vegetation.
4. Use of Sand Blocks and Physical Barriers
   Implementation of filter layers, impermeable materials, and drainage zones to diffuse water flow and control erosion pathways.



Source: Ipswich Planning Scheme, 2016

Figure 2.2.20 Use of Sand Blocks and Barriers for Flow Control

5. Use of Non-Dispersive Topsoil and Vegetative Restoration
   Capping dispersive soil with non-dispersive topsoil (minimum thickness: 150 mm) and implementing vegetative cover, especially on steep slopes, to stabilize the surface.

3) Checklist of Recommended Management Measures (Examples):

- Gypsum Application: Apply in high-erosion zones; avoid near waterways.
- Minimize Exposure Time: Use phased construction to reduce the duration dispersive soils are exposed.
- Runoff Management: Divert stormwater away from dispersive soils toward vegetated or stable zones.
- Rainwater Collection: Use tanks to reduce concentrated discharge from built surfaces.
- Surface Covering: Apply non-dispersive soil or geotextile to protect exposed surfaces.
- Vegetation Regeneration: Essential for surface stability, especially on inclined terrain.
- Diffuse Discharge: Avoid point discharge; spread flow over broader areas to prevent erosion.

2.2.5 Other Dispersive Soil Countermeasures and their Applicability

To date, no universally established countermeasure exists for dispersive soils, and various stabilization methods have been implemented based on local conditions in areas where dispersive soils are known to occur. In addition to the conventional measures described previously, lime stabilization, SPP (sulfonated petroleum product) treatment, and biostabilization using algae have been proposed and, in some cases, practically applied.

Where the deformation risk associated with dispersive soils can be appropriately anticipated, landslide control technologies may also be applicable to international projects. The potential applicability of such technologies should be assessed based on site-specific geotechnical and environmental conditions.

[Explanation]

The lime-based measure is one of the chemical stabilization treatments, in which lime is added to reduce dispersion. In the case study of the Ghotvand Irrigation Project (Iran), dispersibility was reduced by adding 3-6% lime to embankment soil with dispersible clay. The results showed that at 3-5% addition, the soil changed to non-dispersible soil and improved strength and erosion resistance, whereas at 6% addition, the strength suddenly decreased at high water head and the risk of piping and collapse increased.

SPP treatment is a chemical stabilization process, in which sodium in the clay is replaced by a sulfone fossil oil product to stabilize the material and has been studied and practiced mainly in the United States.

Biostabilization with algae is a method in which a naturally occurring “bio-seal” is formed on the surface layer by the establishment of algae, which is expected to provide surface protection and immobilization of fine particles through root systems and mat structures.

Although there is an abundance of basic research and experimental reports on many dispersible soils, there are few reports on specific successes and failures in actual construction. This is due to the diversity of regional, climatic, and host rock characteristics of dispersive soils, which makes generalization difficult. It is important to accumulate and share actual performance data in the field in the future.

2.2.6 Important Points for Consultants and Contractors

> The consultant is responsible for identifying the presence of dispersive soils at the planning, investigation, and design stages. This involves conducting appropriate field and laboratory investigations, performing risk assessments, and proposing design countermeasures as necessary to minimize the hazards associated with soil dispersion. The selected countermeasures must be clearly incorporated into the bidding documents, allowing the contractor to appropriately estimate costs, taking into account required tests, quality control protocols, and construction practices.
>
> During the construction supervision phase, it is essential to verify that the countermeasures are being implemented in accordance with design specifications, and that proper quality assurance is maintained through on-site and laboratory testing.
>
> The contractor must fully understand the nature and risks associated with dispersive soils and ensure that all construction activities are carried out in accordance with the contract documents, while performing the required testing and quality control procedures.

[Explanation]

2.2.6.1 Key Points for the Preparation of Bidding Documents

When dispersive soil is present or suspected at the project site, the following aspects should be carefully addressed in the bidding documents:

- Quality Control Testing:
  If the surrounding area survey suggests a risk of dispersive soil in fill material, the bidding documents must define the appropriate quality control test methods (e.g., pinhole test, crumb test), reference threshold values, and testing frequency. These should be specified in technical specifications.
- Construction Base Verification:
  When dispersive soils are suspected under roadbeds or structure foundations, specifications should include provisions for recording photographic evidence of the construction base and conducting on-site verification and approvals prior to proceeding with works.
- Technical Expertise and Design Considerations:
  Since technical guidance and construction experience with dispersive soils is less developed than that for conventional soils, thorough literature review and site-specific research must be conducted. Planning and design should reflect this, including evaluation of testing feasibility and construction constraints.
- Soil Replacement Details:
  When replacing dispersive soil with higher quality materials, clearly define the horizontal extent and replacement depth on drawings. Specifications must address water management, material quality standards, and compaction criteria for backfill materials.
- Soil Improvement Measures:
  If chemical or mechanical soil improvement is planned, the specifications should define the type of stabilizer, required mix ratios, mixing methods, and testing criteria to verify performance.

2.2.6.2 Considerations for Quality Control During Construction

Engineers engaged in construction management must possess a thorough understanding of the characteristics and risks associated with dispersive soils. Dispersive soils are highly vulnerable to infiltration of surface water and groundwater, which can lead to suspension of clay particles, even under static water conditions. This may result in progressive deformation, settlement, and loss of strength. Therefore, it is critical that appropriate quality control measures be implemented throughout all stages of construction.

Prior to the commencement of construction, it is essential to confirm and document the physical characteristics of dispersive soils (e.g., color, plasticity, consistency). Although dispersive soils cannot be readily identified by visual inspection alone, they typically become muddy upon contact with water due to rapid dispersion of clay particles. Visual and tactile assessments should be employed to assist in field identification.

Key considerations during construction include:

- Drainage Management:
  Dispersive soils are highly sensitive to moisture ingress, which can compromise structural integrity. Localized seepage, springs, or leakage from utility lines should be carefully identified and addressed through proper drainage planning and site-specific water control measures.
- Protection Against Infiltration:
  Even minor surface erosion or subsidence can escalate due to continued wetting. To mitigate this, measures such as covering embankments and cut slopes with protective sheeting should be implemented to prevent direct rainfall infiltration and surface runoff during construction.
- Instrumentation and Monitoring:
  Considering the deformation potential of dispersive soils, the need for dynamic observation should be evaluated. This may include installation of settlement plates, displacement markers, or inclinometers. If significant displacement or deformation is detected, appropriate remedial actions must be taken based on structural impact assessments.

2.2.7 Actions to Be Taken at the Maintenance and Management Stage

In regions where dispersive soils are present, systematic maintenance and management are essential to ensure that the constructed facilities continue to perform their intended functions. Although large-scale deformation may occur, precursors such as minor cracks or surface depressions often appear beforehand. Therefore, during the maintenance stage, it is necessary to conduct daily visual inspections to detect early signs of distress, including cracking, differential settlement, or pavement heave.

Maintenance activities should be planned and implemented by referencing detailed records from previous stages of investigation, design, and construction.

[Explanation]

(1) Objectives of Maintenance

The objective of maintenance is to ensure that constructed infrastructure (such as roads, canals, and buildings) maintains its functional and structural integrity after completion.

In areas where dispersive soil is distributed, as shown in Section 2.2.2 ("Examples of Problem Soils Encountered in Past Construction Projects"), potential failures may include:

- Surface settlement or sliding of embankments and pavements,
- Pavement cracking or collapse,
- Tunnel or culvert erosion,
- Surface erosion and structural weakening of cut or fill slopes.

Such deformation should be identified at the earliest possible stage, and timely corrective measures should be implemented to prevent further damage.

(2) Key Points for Maintenance Planning

Deformations caused by dispersive soils may occur either shortly after construction or several years later, depending on environmental and hydrological changes.

Road infrastructure is particularly vulnerable, as pavement distress can critically impair function. Therefore, when signs of deformation (e.g., cracking, differential elevation, or sinkholes) are observed during routine inspections, it is important to:

- Review historical data from site investigations, design records, and construction reports,
- Estimate the extent and progression of expected deformation,
- Plan and implement appropriate remedial and control measures.

(3) Inspection and Monitoring

The purpose of regular inspection is to detect early-stage structural anomalies that could lead to severe damage if left unaddressed. Inspectors should:

- Identify high-risk zones based on previous experience and known dispersive soil locations,
- Focus inspections on areas where cracking, subsidence, or erosion is likely (e.g., road surfaces and cut slope faces).

In the case of ODA (Official Development Assistance) projects, it is essential that the implementing agency:

- Establish standard daily inspection routines prior to project handover,
- Document key monitoring checkpoints and inspection protocols, and
- Ensure that the information is clearly communicated to maintenance authorities to facilitate effective long-term infrastructure management.

2.3 COLLAPSIBLE SOIL

2.3.1 Summary

Collapsible soils are a type of problem soil characterized by a sudden loss of structural integrity due to external factors such as moisture infiltration or increased loading, resulting in rapid volumetric reduction and subsidence. These soils are typically found in arid and semi-arid regions and are formed from materials such as debris flows, loess, aeolian deposits, and residual tropical soils.

Collapsible soils exhibit an open, porous structure with low dry density yet retain relatively high strength in a dry state. Consequently, during excavation or dry-season construction, cut slopes and excavated surfaces may appear stable. However, the introduction of moisture—through rainfall, fluctuations in groundwater, or surface water infiltration—can lead to a breakdown of interparticle bonding, causing significant settlement or even large-scale slope failures. Such behavior has been documented to cause damage to various infrastructure including buildings, roads, levees, and dams.

While the consequences of collapsible soil behavior can be severe, few comprehensive standards or engineering guidelines exist due to the localized and variable nature of their distribution. As such, it is critical to understand the geotechnical mechanisms underlying collapse and to incorporate appropriate investigation, planning, design, and construction methodologies in affected regions.

[Explanation]

2.3.1.1 Characteristics of Collapsible Soils

(1) General Characteristics

Collapsible soils are typically defined by the following geotechnical properties:

- Open, metastable fabric
- High porosity and low dry density
- Geologically young or recently disturbed deposits
- High moisture sensitivity
- Low natural interparticle bonding strength

The structural integrity of collapsible soils is primarily maintained by capillary tension and minor amounts of cementing agents (e.g., calcium carbonate). These bonding agents are often silt or silty clay, which deteriorate under wetting. When external loading exceeds the strength of the bonding material—or when the bonding agent is weakened due to moisture increase—collapse occurs, accompanied by a rapid rearrangement of soil particles into a denser state.

This behavior is especially pronounced in soils containing silt as a bonding matrix, which exhibits low plasticity and readily undergoes strength loss with minor changes in moisture content. While collapse may result from both applied stress and wetting, moisture infiltration is generally the predominant cause.

(2) Origin and Parent Materials

Collapsible soils can be classified according to their depositional origins, with common types including loess, sandy loam, volcanic ash-derived soils, and Pleistocene alluvial deposits:

- Loess: Aeolian silt deposits consisting primarily of quartz particles weathered under cold conditions, transported by rivers, desiccated, and redeposited by wind.
- Sandy loam: Fine-grained alluvial sediments from floodplains or Pleistocene terraces that collapse upon wetting and/or vibration.
- Volcanic ash soils: Comprised of wind-blown ash and pumice with angular, lightweight particles and high interparticle voids. In Japan, “Shirasu” and unconsolidated tuff are representative.
- Glacial deposits: Rock flour and fine sediments deposited by glaciers and subsequently redistributed by wind; similar in behavior to loess but found in higher latitudes.
- Desert sediments: Wind-deposited sands and silts in arid regions with extremely weak bonding and high moisture sensitivity.

Unlike chemically weathered soils, collapsible soils are primarily the result of mechanical deposition by wind, water, glaciers, or volcanic activity. Consequently, their mineral composition varies, but typical parent materials include:

- Quartz (SiO_2): Resistant to weathering; dominant mineral in most collapsible soils.
- Feldspar (e.g., $KAlSi_3O_8$): Moderately weatherable; common in young alluvial deposits.
- Calcium carbonate ($CaCO_3$): Prevalent in arid-region loess; contributes to temporary bonding.
- Clay minerals (e.g., kaolinite, montmorillonite): Occur as secondary minerals, influencing collapse sensitivity.

2.3.1.2 Structure and Collapse Mechanisms

Collapsible soils undergo sudden volumetric reduction when subjected to external loads in conjunction with the weakening or loss of interparticle cohesion. This cohesion typically includes capillary forces and chemically induced bonding, both of which deteriorate upon moisture infiltration. The resulting loss of structural integrity leads to rapid compaction of the soil matrix, causing significant settlement and, in some cases, slope failure.

2.3.2 Examples of Collapsible Soils Encountered in Past Construction Projects

Collapsible soils have caused a wide range of structural and geotechnical problems in past construction projects. Typical examples include large-scale landslides, deformation and cracking of buildings, severe surface cracking and differential settlement of pavements, and embankment settlement or failure of cut-and-fill slopes. These issues often manifest unexpectedly due to various triggers, such as topographic modifications during construction, fluctuations in surface and groundwater levels following heavy rainfall, dynamic loads from vehicular traffic, seismic activity, or a combination of these factors.

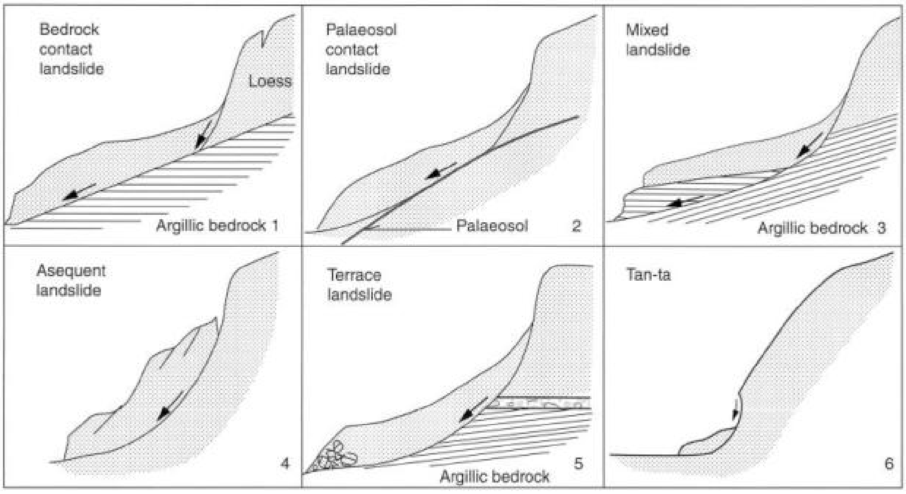
Damage induced by collapsible soils is frequently severe and can result in significant functional disruption and structural impairment of engineered facilities. As such, it is essential to conduct comprehensive investigations, robust design studies, careful construction execution, and diligent post-construction maintenance when implementing infrastructure projects in areas underlain by collapsible soils. By examining case histories presented in this section, it is possible to compile reference examples relevant to the project site and formulate appropriate engineering responses.

[Explanation]

2.3.2.1 Slope Stability, Landslide Types, and Damage Cases

Extensive landslides have repeatedly occurred in regions dominated by loess deposits, such as Central Asia and the Loess Plateau in Gansu Province, China. Landslides in these areas exhibit diverse mechanisms. In some cases, slip surfaces develop at the interface between the loess layer and the underlying subsoil; in others, the failure occurs entirely within the loess stratum. There are also complex failure modes involving multiple factors. Frequently, landslides are initiated by subsidence at the head of a potential failure surface or by water infiltration through surface fissures formed by gully erosion, which ultimately evolve into well-defined slip planes.

Figure 2.3.1 illustrates the principal types of loess-related landslides. Notably, type 6 in the figure represents minor collapses, characterized by diameters less than 10 meters and depths of a few meters, commonly occurring on steep loess slopes. These small-scale failures can evolve into rapid mass movements once initiated, often progressing at high velocities.



Source: ICE Manual of Geotechnical Engineering 2nd Edition Volume 1, Geotechnical Engineering Principles, Problem soils and Investigation, Michael Brown, John Burland et al. (2024)

Figure 2.3.1 Major Types of Landslides in Loess Deposits

Figures 2.3.2 and 2.3.3 present photographic documentation of structural deformation and erosion-related damage observed in collapsible loess terrain, including slip failures. When undertaking engineering works in such environments, it is crucial to recognize that failure mechanisms associated with subsidence in collapsible soils can be extensive and require substantial countermeasures.

Source: Loess Landslides – Peculiarities of Deformation Mechanism, Oleg V. Zerkal and Olga S. Barykina

Figure 2.3.2 Landslide Failure in Loess Deposits

Source: A Modified Collapse Test for Gypseous Soils, Safa Hussain Abid Awn, 2010

Figure 2.3.3 Collapse of Collapsible Gypseous Soil

2.3.2.2 Examples of Damage to Roads (Pavements and Structures)

Transportation infrastructure—particularly roads and railways—is frequently affected by collapsible soils. On roadways, the most common manifestations include differential settlement along the alignment and uneven subsidence due to irregular moisture infiltration into the road subgrade. These phenomena result in undulating or rippled pavement surfaces, which can extend over long distances and cause extensive structural deterioration.

Railways are even more susceptible to settlement-induced issues due to stringent tolerances for longitudinal deformation. Even minor differential settlement can disrupt alignment and compromise operational safety. Similarly, pipelines are vulnerable when lacking sufficient flexibility to accommodate differential longitudinal or lateral movements. The failure of water supply or sewage pipelines due to differential settlement can exacerbate collapse phenomena by introducing additional sources of infiltration.

Structural components such as bridges, cut slopes, and embankments are also at risk. Although stress from overburden and vehicle loading is typically within design limits, the presence of moisture can reduce soil strength significantly. In such cases, even transient loads from heavy vehicles may trigger settlement or collapse of the supporting ground.

Most collapsible soils exhibit high permeability and strong water absorption capacity, necessitating strict drainage management. Inadequate drainage can lead to unexpected settlements, potentially affecting the performance of associated facilities.

Figures 2.3.4 and 2.3.5 illustrate pavement failures and surface subsidence resulting from collapsible soils. Figures 2.3.6 and 2.3.7 show additional examples from Central Asia, where loess is prevalent. These include erosion advancing to the edge of a roadway and landslide-like deformations causing severe displacement of a bridge substructure—ultimately leading to girder removal and abandonment of the structure.

Source: Evaluation of groundwater effects on tunnel engineering in loess, W. Sun, Q. Liang, S. Qin, Y.N Yuan & T. Zhang , 2021

Figure 2.3.4 Settlement of loess and gully erosion

Source: A MODIFIED COLLAPSE TEST FOR GYPSEOUS SOILS, Safa Hussain Abid Awn, 2010

Figure 2.3.5 Collapse of collapsible gypsum soil

Source: JICA Study Team

Figure 2.3.6 Erosion of loess ground

Source: JICA Study Team

Figure 2.3.7 Damage to bridge due to loess ground and deformation

2.3.2.3 Examples of Damage to Buildings and Houses

Figures 2.3.8 and 2.3.9 present examples of structural damage to residential buildings constructed on collapsible soils. Similar to roadways and other infrastructure, buildings situated on collapsible ground are susceptible to localized collapse and differential settlement induced by moisture infiltration. Such geotechnical behavior has led to observable structural damage, including foundation settlement, wall cracking, and in severe cases, partial wall collapse.

Differential settlement caused by uneven wetting conditions—whether from rainfall, groundwater rise, or leaking utilities—results in stress concentrations at the foundation level, which transfer to superstructures and compromise structural integrity. Damage can be progressive and may not manifest immediately following construction, making post-construction monitoring essential in regions where collapsible soils are known or suspected.

Source: Egyptian Collapsible Soils and their Improvement, Mohamed Sakr, Mohsen Mashhour, Adel Hanna, 2008

Figure 2.3.8 Damage to houses caused by collapsible soil (Egypt)

Source: A MODIFIED COLLAPSE TEST FOR GYPSEOUS SOILS, Safa Hussain Abid Awn, 2010

Figure 2.3.9 Cracks in a building on a collapsible gypsum land base

2.3.3 Responses during the Planning and Investigation Phase

During the planning and investigation phase, it is essential to assess whether collapsible soils are present at the proposed project site and to evaluate the need for countermeasures. Given their formation process, collapsible soils are typically distributed in arid and semi-arid regions. It is necessary to assess regional risks using the collapsible soil distribution and hazard risk maps provided in this manual. Site-specific collapsibility should be evaluated through a combination of geological reconnaissance, damage case studies (e.g., nearby slope failures), and appropriate geotechnical investigations and laboratory tests. Project teams are encouraged to prepare risk maps specific to the project area.

Available methods to identify collapsible soils include laboratory tests—primarily oedometer-based collapse potential testing and loading tests under dry and wet conditions—and field tests such as plate load tests and cone penetration tests (CPT). However, standardized testing procedures and evaluation criteria are not yet fully established and may vary by researcher and region. Therefore, investigation and testing methods must be carefully selected and implemented in accordance with the risk level anticipated at the site, with the goal of minimizing catastrophic or large-scale failure risks.

[Explanation]

2.3.3.1 Distribution of Collapsible Soils

Collapsible soils are estimated to cover approximately 10% of the Earth’s surface. Five major global loess regions have been identified: the Midwestern United States (Prairie Region), South America, Europe (including Germany, Eastern Europe, and western Russia), Central Asia, and China. Other affected countries include Nigeria, Kazakhstan, Australia, South Africa, Zimbabwe, Egypt, and Iran. These areas often underlie densely populated zones and key infrastructure, rendering them particularly susceptible to geotechnical hazards such as sudden collapse.

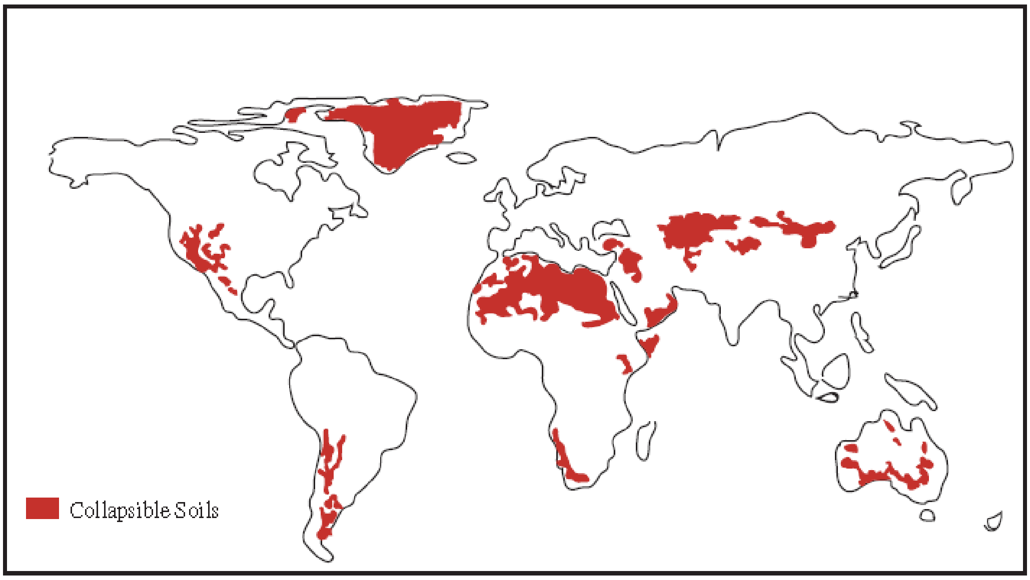
A summary of major collapsible soil types and their geographic distribution is presented in Table 2.3.1.

Table 2.3.1 Major Regions by Soil Classification for Collapsible Soils

Soil Classification	Major Regions
Aeolian Deposits (Loess)	Loess Plateau (China, Mongolia); Central Asia (Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan); Iran, Iraq; Midwest USA (Prairie Region); Europe (Germany, Eastern Europe); Africa (Egypt, Sudan, Algeria, Morocco, South Africa, Nigeria, Ethiopia, Kenya)
Fluvial Deposits	Major river basins in Asia (Ganges, Mekong, etc.); Europe (Danube, Rhine, Ill rivers); USA (Mississippi, Colorado rivers); South America (Amazon River basin)
Volcanic Deposits	Japan (Kanto Loam Formation); Volcanically active regions such as Indonesia and the Philippines
Glacial Deposits	Northern Europe (Norway, Sweden); Northern Canada and Alaska
Desert-Origin Deposits	Gobi Desert, areas surrounding the Sahara Desert; Middle East regions; Australia (Great Sandy Desert, Simpson Desert)
Others	South Africa (Calcrete, a weathering product of limestone); Soils around salt lakes (saline soils)

Source: JICA Study Team

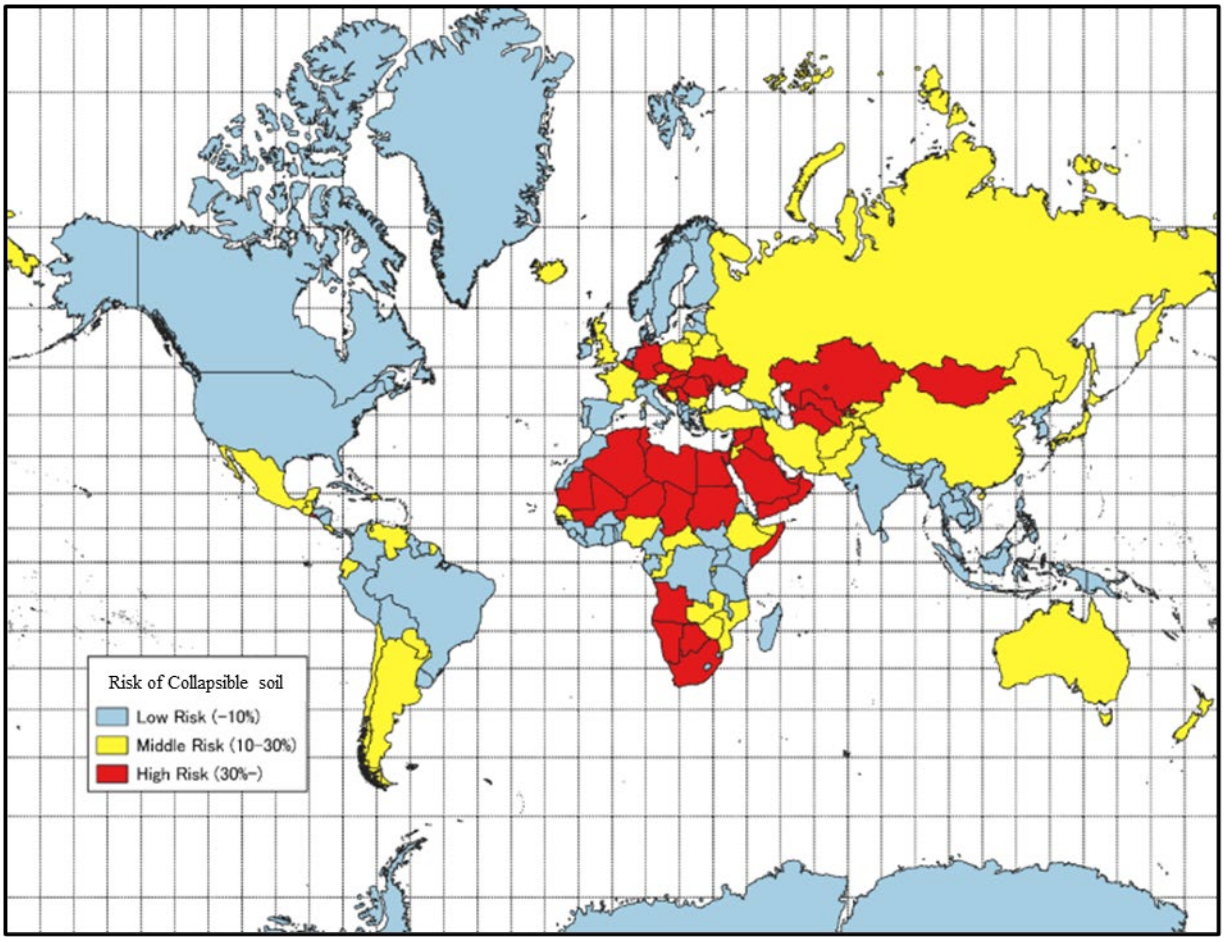
A map of the global distribution of collapsible soils is shown in Figure 2.3.10.



Source: Hydro-Mechanical Analysis of Unsaturated Collapsible Soils and their Stabilization, AhmedAl-anabi(2014)

Figure 2.3.10 Global Distribution of Collapsible Soils

Based on the distribution map shown in Figure 2.3.10 and other data, the percentage of area distributed in each country is calculated, and the percentage of area in each country is calculated and illustrated as the degree of risk, as shown in Figure 2.3.11. If a project is to be implemented in a country that is considered to be at risk, referring also to this figure, a thorough investigation should be conducted to determine the presence or absence of collapsible soil.



Source: JICA Study Team

Figure 2.3.11 Distribution Risk of Collapsible Soils (Loess)

2.3.3.2 Methods for Determining Collapsible Soils

To facilitate the implementation of economical and effective countermeasures, four procedural steps are recommended:

- Specific Identification: Determine whether collapsible soils are present at the site.
- Classification: Categorize the severity or type of collapsible soil problem.
- Quantification: Assess the magnitude of collapse potential and structural disintegration.
- Evaluation: Evaluate appropriate countermeasure methods through engineering design.

A major challenge with collapsible soils is that their existence and the severity of their collapse potential often remain undetected prior to construction. Therefore, it is essential to first identify potentially collapsible soils and then estimate their collapse potential—particularly on sites with water-sensitive soils.

Engineers frequently misidentify, or are unaware of, collapsible soils. Standard geotechnical classification practices tend to group fine-grained materials (e.g., silts and clays) under generalized descriptors, which makes it difficult to identify collapsible soils. Relying solely on such classification systems can hinder proper diagnosis and evaluation. Although considerable global research and case data exist for problem soils, the use of unfamiliar terminology and interdisciplinary knowledge often becomes a barrier to field identification by engineers and technicians.

The following steps are considered appropriate for identifying and characterizing collapsible soils:

1) Preliminary Investigation for Collapsible Soil

Information on the geology and topography of the target area and information on damage cases related to infrastructure facilities will be collected. In addition, information on moisture supplied to the target area, such as rainfall and surface water pathways, will be analyzed.

2) Preliminary Judgement Based on Soil Property Parameters

The potential for collapsed soil is evaluated based on reference values and indicators based on soil properties such as natural moisture content, void ratio, and Atterberg properties. It should be noted that many of these indices have low correlations and high variability, making them less judgmental, and should be used as a guide for making decisions.

3) Laboratory Testing

Collapse testing using a consolidation tester and evaluation metrics based on the test results have been proposed by ASTM and other researchers. Other methods have been proposed, such as consolidation testers capable of measuring suction, Rowe Cells, triaxial collapse tests, and double hydro tests.

4) Field Testing

The Sausage Test has been proposed as a simple method for determining collapsible soil in the field, and other methods for determining collapsibility have been proposed based on evaluation of the results of flat plate loading tests, electric cone penetration tests, horizontal borehole loading tests, standard penetration tests, and cone penetration tests.

2.3.4 Measures to be Taken at the Design and Construction Stage

If collapsible soils are identified during the investigation phase, appropriate mitigation measures must be considered to minimize the risk of deformation during and after construction. The failure of collapsible soils can result in widespread subsidence, landslides, and other forms of large-scale damage. Therefore, a safe and rational project design must incorporate consideration of potential risks from the initial planning and design phases, including road alignment and structural layout.

As collapsible soil failures—such as settlement or slope instability—are predominantly caused by increased water content, particular attention should be paid to drainage control within the influence zone of the structure. Countermeasures may include:

- Replacement of collapsible soil,
- Control of surface and subsurface water infiltration,
- Ground densification techniques (e.g., dynamic compaction, vibroflotation),
- Chemical stabilization using cement or other binding agents.

During the design phase, parameters such as the required thickness of the replacement layer, type and mix ratio of stabilizing agents, and application boundaries should be clearly defined. These should be documented in the design drawings and supported with detailed construction specifications and quality control criteria.

During the construction phase, great care should be taken to minimize risk in strict accordance with the design documentation. Quality control should be conducted in line with the specifications and tailored to the purpose of the countermeasure. Furthermore, given the regional variability in the behavior of collapsible soils and the potential for countermeasures to perform differently than expected, it is advisable to incorporate trial construction segments based on the assessed risk level.

[Explanation]

2.3.4.1 Considerations for the Design of Countermeasure Works and Method Selection

When designing countermeasure works, it is essential to select methods based on:

- Experience and engineering judgment regarding in-situ soil behavior,
- Applicability limitations of candidate methods,
- Constructability and practicality,
- Project scale, use, and structural performance requirements,
- Environmental considerations,
- Cost-effectiveness and economic comparison of available methods.

Given the susceptibility of collapsible soil layers to moisture infiltration-induced deformation, a comprehensive construction plan should be developed, including drainage management strategies, temporary construction yards, and treatment of construction effluents, with appropriate cost estimation.

2.3.4.2 Considerations for Quality Control During Construction

Construction engineers must fully understand the behavior of collapsible soils and how fluctuations in surface and groundwater influence soil strength and stability. Appropriate attention must be given throughout the construction process. The following considerations are particularly important:

- Collapsible soil can cause settlement or a decrease in shear strength due to water seepage into the ground or unexpected fluctuations in groundwater, which can damage structures. Particular attention should be paid to localized spring water or existing pipes during construction, and appropriate measures should be taken after considering the impact.
- During construction, the need for dynamic monitoring (installation of subsidence plates, installation of displacement piles, etc.) will be considered in light of the characteristics of collapsible soil. If dynamic monitoring is conducted and the measurement results show any deformation of the collapsible soil layer, necessary measures will be implemented after considering the impact on the structure.
- When constructing facilities in areas with collapsible soil layers, it is useful to frequently record the construction status in order to consider countermeasures in the event of an unexpected event. In addition, keeping construction data and quality control records as data is useful for avoiding risks related to expansive soil in the implementation of future projects and for the development of research, so it is desirable to actively record the construction status, leave the data with the implementing organization, and share it with related parties through presentations in the academic community, etc.

2.3.5 Other Technologies and Applicability for Dealing with Collapsible Soils

There are no universally established countermeasures for collapsible soils. Various measures have been adopted in regions where collapsible soils are prevalent. In addition to the previously discussed methods, techniques such as pre-wetting, sintering, and the application of geosynthetics have been proposed and implemented in specific cases.

Where the risk of ground deformation due to collapsible soils can be appropriately identified, conventional landslide control technologies may be applicable to international projects, and their potential use should be assessed accordingly.

[Explanation]

The pre-wetting method is a method of flooding or wetting soil that is expected to collapse due to water infiltration prior to structure construction, so that soil collapse is minimized after structure construction. Soil wetting can be accomplished by ponding or by using trenches or boreholes. The pre-wetting method is effective when induced loads are small, such as in waterways and roads, but must be used in conjunction with preloading to prevent future foundation settlement.

The sintering method was developed to improve the collapse characteristics of yellow soil and mainly uses high temperatures. Although there have been some experiments with good results, the cost is high and there have been few applications.

Thus, in areas where collapsible soils are distributed, efforts are being made to take countermeasures. In the planning stage of a project, the applicability and risks of local countermeasures, if any, should be analyzed and reflected in the project plan.

If there is a risk of landslide due to the collapse of collapsible soil in the area where the collapsible soil is distributed, the application of landslide countermeasures should be considered. In many areas, collapsible soils are thickly accumulated, and the scale of the landslide countermeasures may be larger than usual in order to be effective. Accurately estimate the risk and plan the necessary countermeasures to ensure function and safety.

2.3.6 Consultant and Contractor Business Considerations

The consultant shall accurately identify the distribution of collapsible soils within the proposed project site during the planning, investigation, and design phases. Investigations and laboratory tests shall be conducted with the objective of minimizing the risks associated with the behavior of collapsible soils. Based on the findings, appropriate countermeasure works shall be planned and designed. These countermeasures must be reflected in the bidding documents, enabling the contractor to estimate the associated costs in accordance with the identified risk, while accounting for necessary testing, quality control measures, and construction considerations. During construction supervision, it is essential to ensure that countermeasures are implemented in compliance with the technical specifications and that construction progress and quality are controlled through appropriate in-situ and laboratory testing.

The contractor shall understand the characteristics and potential risks associated with collapsible soils and shall execute construction activities with due consideration of these factors, while performing necessary testing and quality control in accordance with the contract documents.

[Explanation]

2.3.6.1 Notes on Preparation of Bidding Documents

When collapsible soils are present within the project site, the following considerations should be incorporated into the preparation of bidding documents:

- If it is determined that collapsible soils may exist beneath pavement subgrades or structural foundations, the technical specifications should include provisions to prevent unexpected risks. These may include requirements for photographic documentation of prepared foundation surfaces and on-site verification and approval processes.
- Technical knowledge and experience regarding countermeasures for collapsible soils are limited compared to general soil engineering practices. Therefore, sufficient research should be undertaken, and detailed testing and construction methods should be planned and incorporated into the design.

- When collapsible soils are to be replaced with higher quality materials, the extent and depth of replacement should be explicitly defined in the construction drawings. The technical specifications should also stipulate requirements for minimizing risk, including water management considerations, material quality standards, and compaction criteria for backfilling.

2.3.6.2 Considerations for Quality Control During Construction

Construction management engineers must fully understand the properties of collapsible soils, particularly their susceptibility to settlement and loss of strength due to moisture infiltration from surface water and groundwater fluctuations. This understanding is essential for ensuring appropriate risk mitigation throughout the construction process. It is also important to visually and physically confirm the characteristics (e.g., color, texture, and other physical indicators) of collapsible soils at the project site prior to construction commencement to ensure accurate identification and handling.

- Collapsible soils may undergo deformation when exposed to moisture, potentially compromising structural integrity. Therefore, drainage management is critical during construction. Special attention should be given to the presence of local water springs or existing pipelines. If such features are present, appropriate measures should be implemented after evaluating the potential impacts.
- Given the behavior of collapsible soils, the necessity of dynamic observation—such as installing settlement plates or displacement gauges—should be assessed. If such monitoring is implemented and deformation of the collapsible layer is observed, remedial measures should be taken after evaluating the structural impact.

2.3.7 Actions to Be Taken at the Maintenance and Management Stage

In regions where collapsible soils are present, appropriate maintenance and management must be implemented to ensure that constructed facilities retain their intended functionality over time. Because signs of deformation typically precede large-scale failures, routine inspections during the maintenance phase should include careful checks and documentation of any observed deformations—such as cracks, differential settlements, or surface depressions—affecting the structures. In addition, considering the mechanisms behind collapsible ground deformation, it is essential to verify and record whether drainage systems are being properly maintained and continue to perform their intended function.

For effective maintenance and management, surveys, inspections, and maintenance operations must be conducted with reference to documented records from the investigation, design, and construction phases.

[Explanation]

2.3.7.1 Maintenance Objectives

The primary objective of maintenance is to ensure that structures—such as roads, waterways, and buildings—continue to perform their designated functions effectively and to preserve the structural safety after construction is complete.

In areas with collapsible soils, as discussed in *Section 2.3.2: Examples of Problem Soils Encountered in Past Construction Projects*, such soils may induce a variety of failures, including settlement or landslides of embankments and pavement surfaces, structural damage, wall cracking, and slip failures of cut and fill slopes. These forms of deformation should be detected as early as possible, and prompt remedial actions must be taken to prevent further deterioration.

(1) Points to Keep in Mind for Maintenance

Structural deformation resulting from collapsible soil behavior can manifest immediately after construction or may take several years to develop. In road infrastructure in particular, pavement distress can significantly compromise the structure's serviceability.

Therefore, when deformation is identified during routine inspections, records from the investigation, design, and construction phases should be reviewed to assess the potential extent and severity of future deformation. Based on this assessment, appropriate deformation control or repair measures should be planned and implemented without delay.

(2) Inspection and Survey

Routine inspections serve to identify early-stage structural deformations that could progress into severe damage and to determine whether corrective measures are warranted. Inspectors should pre-identify areas of concern and focal points for observation based on known cases of collapsible soil-related failures.

For road structures, attention should be paid to progressive longitudinal cracking in pavement surfaces and to deformation in cut slopes. In the context of Official Development Assistance (ODA) projects, it is essential to compile a summary of inspection and survey protocols—including daily monitoring tasks and key observation items—that should be performed by the project operator prior to handover. These procedures must be clearly communicated to ensure that adequate maintenance and management practices are upheld.

2.4 LATERITE

2.4.1 Summary

Laterite is a highly weathered residual soil rich in iron and aluminum oxides, commonly exhibiting a reddish-brown color due to the presence of hematite and goethite. It is predominantly found in tropical and subtropical regions characterized by hot and humid climates. Although the term "laterite" is widely used in geotechnical engineering, its definition remains somewhat ambiguous across disciplines such as mineralogy, pedology, and civil engineering.

Laterites range in consistency from hard, rock-like masses to soft, friable soils with a wide variation in texture, density, porosity, and engineering behavior. These properties can vary significantly depending on the origin, formation environment, and degree of weathering.

In many regions, lateritic materials are extensively used in construction—both historically and in contemporary engineering practices. Applications include building bricks, road embankment material, subgrade fill, and as aggregates for concrete. Despite this utility, lateritic soils exhibit considerable variability in key geotechnical parameters such as grain size distribution, Atterberg limits, natural moisture content, compaction characteristics, and shear strength. Consequently, proper sampling, handling, and testing protocols are essential to ensure reliable application in engineering works.

[Explanation]

2.4.1.1 Features of Laterite

(1) General Characteristics

Laterite lacks a single universally accepted definition, but it is generally considered a weathering product of ferromagnesian or alumino-silicate rocks in hot, humid environments. According to common classifications from previous studies, a soil or rock is generally considered laterite if it meets the following four criteria:

- Geographic Distribution: Found in tropical to subtropical climatic zones (including relict tropical paleoenvironments).
- Topographic Setting: Formed in areas with sufficient elevation, gentle slopes, or plateau conditions facilitating surface runoff.
- Physical Consistency: Occurs as either a hardened, indurated lateritic crust (laterite proper) or as granular/massive, poorly cemented lateritic soils.
- Chemical Composition: Enriched in sesquioxides, especially iron oxide (Fe_2O_3) and aluminum oxide (Al_2O_3).

This handbook focuses on lateritic soils as defined from a geotechnical engineering perspective—i.e., those materials encountered during construction that exhibit engineering behavior affected by their lateritic origin, regardless of whether they are indurated or not.

(2) Origin / Parent Material

The genesis of laterite is closely tied to intensive chemical weathering of diverse parent rocks under tropical climatic conditions. Lateritic soils have been identified over a wide range of lithologies including:

- Igneous rocks: Granite, granodiorite, basalt, rhyolite
- Metamorphic rocks: Gneiss, schist, phyllite
- Sedimentary rocks: Sandstone, shale, limestone

- Volcanic deposits and ash layers

The essential prerequisite is the availability of a source of iron or aluminum (either in situ or from upslope transport), combined with intensive leaching that removes soluble bases while leaving behind residual oxides.

(3) Formation Process

Laterite forms through progressive chemical weathering and leaching under high rainfall and temperature conditions. The typical sequence of laterite formation is summarized in the following table:

Table 2.4.1 Laterite Formation Processes

Weathering Process	Description
Initiation of Chemical Weathering	Under warm and humid conditions, minerals within the parent rock undergo chemical reactions involving water, carbon dioxide, and oxygen, leading to decomposition. Silicate minerals (e.g., feldspar, pyroxene) are hydrated and hydrolyzed, resulting in the leaching of silica.
Leaching	Silica and base cations (potassium, calcium, sodium, magnesium) dissolved in water are flushed downward by rainfall. Iron (Fe) and aluminum (Al) oxides remain concentrated in the residual material.
Accumulation	Iron and aluminum oxides are oxidized and form hardened red oxides. These oxides constitute the bases for iron ore (Fe_2O_3) or bauxite (Al_2O_3) deposits.
Induration	Repeated cycles of wetting and drying over extended periods cause iron and aluminum oxides to bind together like cement, forming a hardened layer.

Source: JICA Survey Team

Factors that influence laterite formation include weather conditions, such as high temperatures and humidity; topographic and drainage conditions, such as the amount of surface water and water infiltrating the ground; the host rock and vegetation environment; and elapsed time.

2.4.1.2 Characteristics of Laterite and Challenges in Construction Projects

(1) Geotechnical Properties and Evaluation of Laterite

1) Physical Properties

Laterite exhibits considerable variability in grain size distribution, ranging from clay-sized particles to gravel and even massive fragments. This heterogeneity, combined with the fragile aggregation of soil particles, means that sample preparation and testing procedures can significantly affect measured values. The disintegration of coarse particles during handling and testing may skew results, particularly in grain size analysis.

Atterberg limits are similarly affected by testing methodology and reproducibility can be poor. Nevertheless, many lateritic soils plot below the A-line on the Casagrande plasticity chart and typically show high plasticity with liquid limits often exceeding 50% and plasticity indices greater than 20.

The natural moisture content of lateritic soils varies widely, from less than 3% to over 200%, depending on their degree of weathering and field conditions. In-situ dry densities also range significantly:

- High-density laterites (homogeneous and well-indurated): 2.08–2.56 g/cm^3
- Low-density laterites (volcanic red clay-like or highly porous): 0.32–0.96 g/cm^3

In African practice, linear shrinkage is used as an evaluation criterion for the suitability of laterite as a road material, with a maximum allowable shrinkage of 5% often specified for use in lower pavement layers.

2) Mechanical Properties

Laterite's compaction characteristics are highly dependent on its initial moisture content, weathering profile, particle composition, and handling methods. Generally:

- When compacted after moistening a dry sample, high dry density is achievable.
- When compacted after drying a wet sample, low dry density results, even at standard compaction effort.

California Bearing Ratio (CBR) values are typically high under dry conditions, but decrease sharply upon wetting. This water sensitivity is further influenced by compaction energy: higher compaction energy can improve strength but also magnify strength loss with moisture increase.

Laterite consists of both hard and soft aggregated particles. Weak aggregates tend to crush under compaction or repeated traffic loads, which increases the proportion of fines and may degrade performance.

Strength characteristics of lateritic soils are influenced by:

- The type of parent rock and its mineralogy
- Degree of weathering and drying
- Local topography and hydrology
- Depth and condition of the depositional environment

(2) Engineering Challenges of Laterite in Construction Projects

Laterite deposits commonly exhibit a three-layer profile:

- Surface hardened layer (ferricrete) – High in iron/aluminum oxides, difficult to break or process
- Underlying gravels and pebbly sand
- Lower clayey transition zone

While the hardened surface crust may be unsuitable for use in embankment fill due to large fragment size, it can often be processed (e.g., crushed and sieved) to yield high-quality material. However, careful particle size adjustment is required to meet design specifications.

In foundation applications (e.g., subgrades of roads or structural bases), engineers must thoroughly investigate the complete vertical profile, including lower sedimentary and clay layers beneath laterite horizons, to assess potential weaknesses or water sensitivity.

Thick laterite layers must also be examined in terms of:

- Spatial consistency
- Material quality across depth
- Volume available for use

Even if a layer appears to consist of high-quality gravely laterite, poor gradation—such as low sand content and high fines—can lead to deformation under traffic loads, particularly shear flow or rutting.

2.4.2 Examples of Laterite Encountered in Past Construction Projects

In regions where laterite is widely distributed, it has been commonly used as a high-quality embankment and subgrade fill material in road construction. However, numerous instances of road damage have also been reported in such areas, raising concerns over the variability of engineering properties in lateritic soils and the lack of standardized evaluation and quality control methods.

These case histories highlight the need for thorough site investigation and careful consideration at every phase of planning, design, and construction when utilizing laterite in infrastructure projects.

[Explanation]

Many national roads in West Africa have exhibited significant surface damage, including:

- Pavement deterioration
- Surface depressions and rutting
- Localized heaving (swelling)

Such deformations have resulted in **serious degradation of ride quality and traffic safety**. These failures are frequently observed on both paved and unpaved laterite roads.

Source: JICA Study Team

Figure 2.4.1 Surface Deformation of Unpaved Laterite Road (Guinea)

Source: JICA Study Team

Figure 2.4.2 Pavement Damage on Guinea's National Highway 1

The probable contributing factors to these failures include:

- Inadequate treatment of underlying soils
- Use of inappropriate or heterogeneous lateritic materials
- Poor control of moisture content and compaction during construction
- Insufficient maintenance and rehabilitation after opening

Even in stabilized sections where cement stabilization was applied, similar problems were observed, such as:

- Pavement cracking and deterioration
- Subgrade failure
- Differential settlement in recycled roadbed layers

Source: Africa (Ethiopia, Ghana, Tanzania) Revised Final Report on Road Improvement Planning through Financing Cooperation Projects (Basic Study)

Figure 2.4.3 Pavement Damage due to Subgrade Deterioration on Laterite Base with Cement Stabilization (Laos)

2.4.3 Response in the Planning and Research Phase

During the planning and site investigation phase, the presence or absence of laterite deposits within the project area must be assessed. In addition, where lateritic soils are confirmed, discussions should be held on the potential use of laterite as a construction material, and necessary countermeasures should be considered accordingly.

Laterite is predominantly distributed in tropical and subtropical climates. In regions where it occurs, laterite is frequently used as a locally sourced construction material for road embankments, subgrades, and other applications. Therefore, at the project planning stage, it is essential to collect and analyze historical data on the use of laterite in past construction efforts—including information on the condition and performance of existing infrastructure—as part of a proactive risk mitigation strategy.

The geotechnical characterization of laterite typically involves general soil testing methods for evaluating physical and mechanical properties. However, some physical characteristics of laterite—such as grain size distribution and plasticity indices—are known to be highly sensitive to sample pretreatment methods and laboratory procedures, and therefore may produce inconsistent or misleading results if not carefully managed.

Moreover, standardized methodologies for assessing the mechanical properties of laterite, such as compaction behavior and California Bearing Ratio (CBR) values, have not been fully established. As a result, field and laboratory investigations should be carefully designed and implemented, and interpretation of results should involve technical consultation with experts familiar with local soil behavior and lateritic materials.

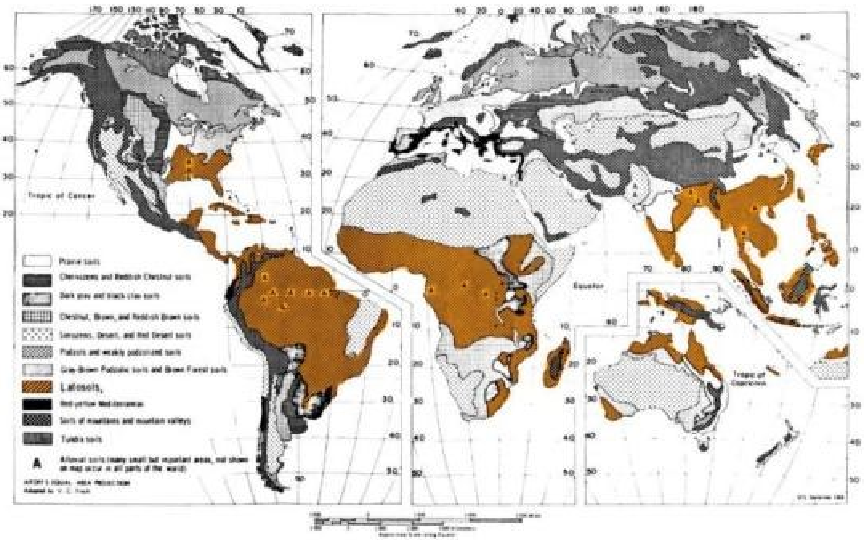
[Explanation]

2.4.3.1 Distribution of Laterite

Laterite deposits are primarily distributed between 35° north and 35° south latitude, in tropical and subtropical climate zones. A global distribution map of laterite based on existing literature is presented in Figure 2.4.4.

Notable countries with known laterite distribution include:

- Africa: Ghana, Nigeria, Côte d'Ivoire, Cameroon, Republic of Congo, Angola, Kenya, Uganda, Tanzania
- Asia: India, Sri Lanka, Thailand, Vietnam, Cambodia, Laos, Malaysia, Indonesia
- Oceania: Australia, Papua New Guinea
- Americas: Brazil, Colombia, Venezuela, Mexico
- Caribbean: Cuba, Jamaica, Haiti, Dominican Republic

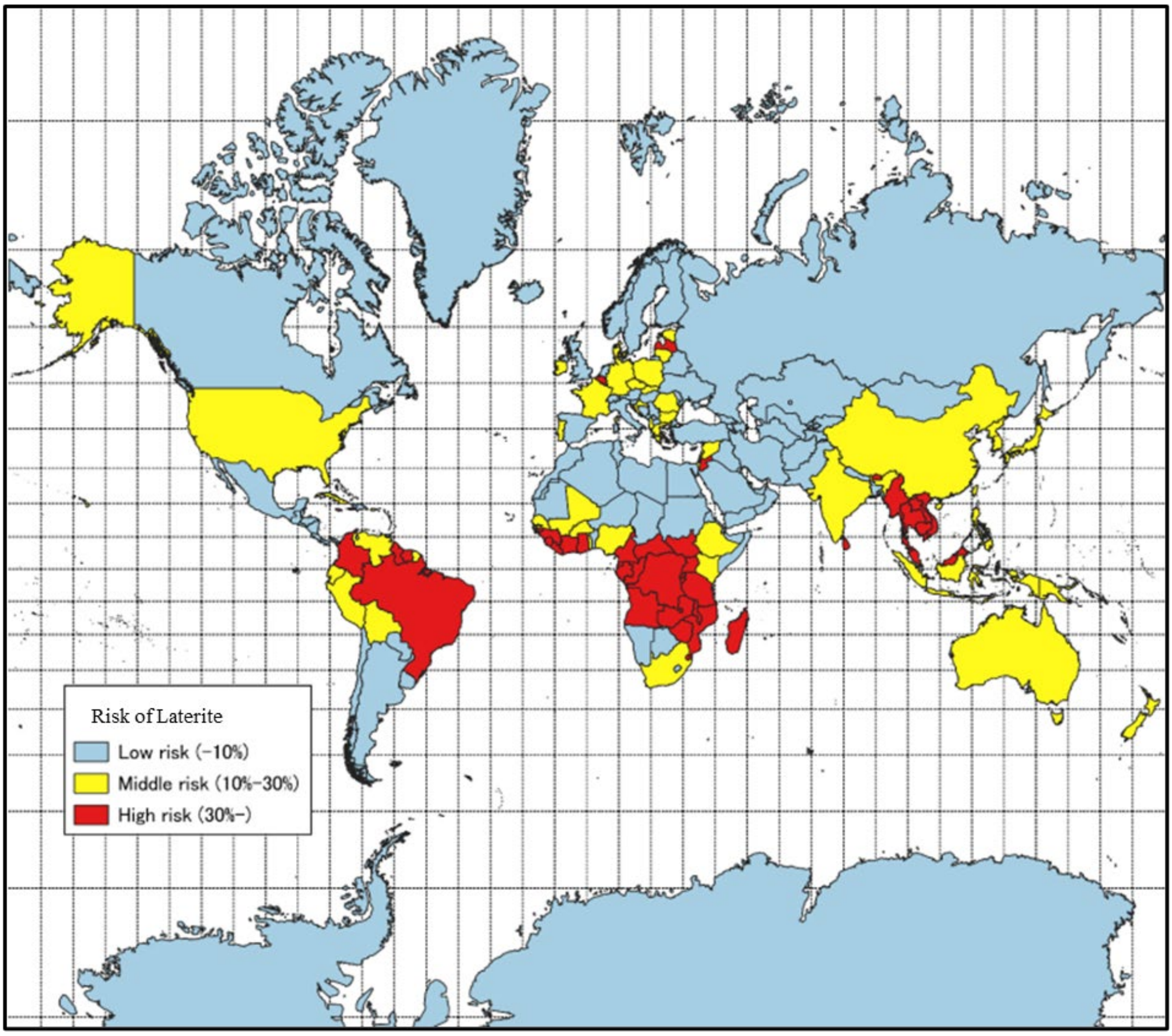


***Source**: An Investigation into the Geotechnical Engineering Properties of Laterite Soils in Nilai, Malaysia, Ahmed Sujeeth (2015)*

Figure 2.4.4 Distribution of Lateritic Soils Worldwide

In addition, based on the data illustrated in Figure 2.4.4, a comparative country-by-country analysis was conducted to estimate the proportional area of laterite distribution, which has been visualized as a laterite distribution risk chart (see Figure 2.4.5).

When implementing infrastructure development projects in countries identified as laterite-prone, it is highly recommended to conduct comprehensive site investigations to confirm the presence, properties, and suitability of lateritic materials, and to assess their potential impact on design and construction.



Source: *JICA Study Team*

Figure 2.4.5 Country-Level Risk Assessment Based on Laterite Distribution

2.4.3.2 Laterite Testing and Determination

Due to the high variability in laterite test results caused by differences in natural moisture content, sample preparation methods, and laboratory procedures, there is currently no unified or standardized evaluation method for laterite. In this section, soil testing indices and evaluation methods—primarily related to the suitability of laterite as a soil material or pavement aggregate—are extracted from existing literature. The following tables (Tables 2.4.2, 2.4.3, and 2.4.4) present classification criteria and engineering evaluations that can serve as practical references when assessing lateritic materials for infrastructure use.

Table 2.4.2 Criteria for Evaluating Lateritic Soils Used Under Asphalt Pavement

Soil Property	Good	Average	Poor
Linear Shrinkage (%)	0–4	4–6	>6
Plasticity Index (%)	0–6	6–8	>12
Liquid Limit (%)	14–21	22–30	>30
Swell from CBR Test (%)	0–0.2	0.3–0.4	>0.4
Optimum Moisture Content (%)	–	8–10	–

Source: Identification of Problem Laterite Soils in Highway Engineering – A Review, M.D. Gidigasu, 1974

Table 2.4.3 Aggregate Performance Evaluation for Lateritic Pavement Materials (West Africa)

Specific Gravity	Water Absorption After 24 Hours (%)	Aggregate Impact Value (%)	Los Angeles Abrasion Value (%)	Evaluation
>2.85	<4	<30	<40	Very Good
2.85–2.75	4–6	30–40	40–50	Good
2.75–2.58	6–8	40–50	50–60	Fair
<2.58	>8	>50	>60	Poor

Source: Identification of Problem Laterite Soils in Highway Engineering – A Review, M.D. Gidigasu, 1974

Table 2.4.4 presents the expected engineering behavior and potential issues during construction associated with lateritic soils based on their physical properties.
By conducting laboratory tests and evaluating the physical and engineering properties, the potential problems of a given lateritic soil can be easily identified.

Table 2.4.4 Engineering Evaluation of Lateritic Soils

Geotechnical Properties			Probable Engineering Behavior and Field Performance				
Laboratory Testing	Average Range of Values		Sensity to Drying	Structure Sensitivity to Remolding	Potential Self-Stabilization	Field Compaction Problems	Degradation Under Traffic and During Compaction
	Unfavorable	Favorable					
Aggregate impact value (%)	>50	<30					☑
Water absorption rate (%)	>8	<4					☑
Natural moisture content (%)	≒liquid limit	Below plastic limit	☑	☑		☑	
Linear shrinkage rate (%)	>6	<4				☑	
Potential swell (%)	>11	<10			☑		
Predominant clay minerals	Montmorillonite; hydrated halloysite	Kaolinite, chlorite	☑	☑		☑	
Mica content (%)	>10	<10				☑	
Aggregation index	>2	≒1	☑	☑			

Source: Identification of Problem Laterite Soils in Highway Engineering – A Review, M.D. Gidigasu, 1974

2.4.4 Measures to be Taken at the Design and Construction Stage

When executing construction projects in regions where lateritic soils are prevalent, it is essential to carefully assess the suitability of the foundation ground, particularly considering the typical stratigraphy—with a hard, shallow laterite crust and softer, finer-grained material in deeper layers. An accurate assessment of whether ground improvement is necessary should be based on this environmental context.

When using laterite as an engineering material, it is important to clearly define material specifications, testing and evaluation procedures for quality control, and construction specifications, including compaction requirements. In practice, replacement is the most widely employed countermeasure where the natural laterite is of poor quality. Where suitable replacement material is not available, in-situ stabilization—using additives such as cement or lime—is also commonly adopted to improve the soil's engineering properties.

During construction, strict adherence to quality control procedures and careful monitoring in accordance with the project specifications are vital.

[Explanation]

2.4.4.1 Design Considerations and Selection of Countermeasure Methods

In selecting countermeasure methods, designers must make decisions based on the following:

- On-site geotechnical experience and judgment;
- Applicability and limitations of each stabilization or replacement method;
- Construction method feasibility;
- Project scale and intended use (e.g., road vs. structure);
- Environmental impacts;
- Cost-benefit comparison of alternatives.

Replacement is typically chosen for poorly performing laterites, especially when softer soil layers (with low Standard Penetration Test N-values) are not prevalent—making deep mixing unnecessary. In these cases, shallow stabilization or replacement within the influence depth of loading is generally sufficient.

However, there is no unified design methodology to determine the required thickness of the replacement layer. Empirical approaches are widely used and vary by region. In pavement design, the replacement thickness is typically determined by considering:

- The proposed pavement structure;
- Soil classification;
- California Bearing Ratio (CBR) values;

This follows standards and guidelines developed in the EU, US, and Japan.

Still, caution must be exercised in interpreting CBR values and soil test data for laterite, as test results can vary significantly due to differences in sample preparation, moisture content, and testing procedures.

Lime and cement are the most commonly used binders for soil stabilization. However, there is no universally accepted design methodology for mix design. Moreover, past cases of deterioration in cement-stabilized laterites have been reported, especially with aging. As with replacement, the long-term performance and durability of the stabilization method must be considered carefully.

2.4.4.2 Considerations for Quality Control During Construction

When managing construction projects that use laterite as a fill or subgrade material, engineers must conduct field verification through:

- Visual inspections to check for consistency with laboratory-predicted characteristics;
- Tactile assessments (by hand) to detect fine-grained content or unexpected variability;
- Frequent in-situ testing, including:
  - Field dry density tests,
  - CBR tests, and
  - Trial pits to verify layering and condition of the subgrade.

Laterite layers can exhibit significant variation in thickness and properties over relatively short distances. Hence, quality control should be performed with sufficient frequency and coverage to detect such variability and adjust the construction plan as necessary.

2.4.5 Other Laterite Countermeasures and Applicability

> In regions where lateritic soils are used in construction, shallow replacement and in-situ improvement techniques are the most commonly applied methods. Beyond traditional approaches, efforts are being made to incorporate cementitious stabilization, lime treatment, and particle size adjustment techniques to enhance the engineering performance of lateritic materials. These advanced or alternative techniques are not yet widely adopted, but their applicability should be explored, particularly when locally available materials or low-cost industrial by-products are present, and when the measures are expected to rationalize construction or enhance long-term performance.

[Explanation]

In addition to lime stabilization and cement stabilization, there have been many studies and trials of economically advantageous stabilization methods that combine materials that would otherwise become industrial waste. Table 2.4.5 shows examples of such methods applied to laterite road construction. If materials are available inexpensively and in large quantities in the region, it is recommended that the optimal method be used after thoroughly confirming its appropriateness by conducting laboratory tests to determine the amount of the material to be blended and by conducting test construction.

Table 2.4.5 Laterite Ground Improvement Methods Adopted for Road Construction

No.	Author & Year	Method / Material Used	Key Findings	Region
1	Attoh-Okine et al., 1995	Laterite + Lime (≤10%) for base/subbase	• Improved secant modulus and shear strength. • Enhanced load-bearing capacity.	Miami, USA
2	Mahalinga-Iyer et al., 1997	Laterite compacted with water to OMC, left open for 14 days before sealing	• CBR: 35–90%. • Shrinkage performance affected by clay minerals (montmorillonite, illite, kaolinite).	Australia
3	Alhassan & Mustapha, 2007	Laterite + Rice Husk Ash (≤8%) + Cement (≤8%)	• MDD: 1.40–1.55 Mg/m³, OMC: 22–32%. • CBR: 30–140%. • UCS: up to 2400 kN/m² (28 days). • Improved CBR due to pozzolanic reaction.	Nigeria
4	Li et al., 2012	Laterite + 5% Cement compacted at 90–96% density	• Deformation depends on compaction, saturation, structure. • CBR: 55% in 24h. • Cement improves compressibility & water resistance.	China
5	Edeh et al., 2012	Laterite (40%) + Reclaimed Asphalt (58%) + Cement (2%)	• CBR: 55% in 24h. • Cement + asphalt improved binding & performance.	Nigeria
6	Biswal et al., 2015	Laterite (silt <30%) as subbase	• Resilient modulus ↑ with OMC and bulk stress (≤275kPa). • CBR: 20–30%. • Minor deformation under triaxial loading.	Odisha, India
7	Kariyawasam et al., 2016	3 types of Laterite + 10% Cement + 6–8 mm chips	• Cement ↓ water absorption. • Chips improve surface resistance for vehicle traffic.	Sri Lanka
8	Saing et al., 2018	Laterite + Lime (10%) with 97.8% CaO	• Vertical deformation ↓ (3.3–8.2 mm). • Subgrade & elastic modulus significantly ↑. • Lime-treated soil ≫ untreated in performance.	Indonesia

Source: Characterization of Laterite Soil and Its Use in Construction Applications - A Review G. Santha Kumar (2022), P.K. Saini, Rajesh Deoliya, Aman Kumar Mishra, S.K. Negi (2022) - Simplified by JICA study team

2.4.6 Important Points for Consultant and Contractor

> The consultant shall accurately determine the presence and extent of laterite at the proposed project site during the planning, investigation, and design stages. Investigations and laboratory testing should be conducted to evaluate the engineering characteristics of lateritic ground and assess its suitability as a construction material. Where necessary, appropriate countermeasure designs shall be developed and incorporated into the bidding documents to enable contractors to make realistic cost estimates based on potential risks.
>
> At the construction stage, the consultant must supervise and confirm that countermeasure works are carried out in compliance with specifications and verify construction status through appropriate quality control testing—including in-situ and laboratory testing.
>
> The contractor shall have a comprehensive understanding of the engineering behavior and potential risks associated with laterite. The contractor must perform construction activities in accordance with the contract specifications, while executing the necessary testing and implementing strict quality control procedures. If expansive behavior is present in lateritic material, appropriate measures should be taken.

[Explanation]

2.4.6.1 Notes on Preparation of Bidding Documents

If laterite is distributed at the project site and is expected to be used either as a fill material or encountered in the foundation layer, the following should be considered in the preparation of bidding documents:

- Identification and Documentation of Laterite Distribution:
  When laterite is expected beneath pavements or foundation structures, the technical specifications should include:
  - ➢ Trial excavations at regular intervals
  - ➢ Procedures for photographic documentation of the subgrade surface
  - ➢ Requirements for on-site verification and consultant approval
    These measures help in accurately determining the horizontal and vertical extent of laterite layers and minimizing unexpected construction risks.
- Specification of Quality Control Methods:
  Since the engineering properties of laterite—especially its compaction and strength characteristics—may vary significantly depending on moisture content, compaction conditions, and handling, the specifications should require:
  - ➢ Post-compaction verification through in-situ tests (e.g., density, CBR)
  - ➢ Material quality tests (e.g., grain size distribution) during construction
  - ➢ Proper documentation of all testing procedures and results
- Foundation Suitability and Replacement Requirements:
  If unsuitable lateritic layers are identified within the construction footprint:
  - ➢ The expected extent of these layers should be marked in drawings
  - ➢ Risk mitigation provisions (e.g., water control, replacement thickness, compaction criteria) should be included
  - ➢ The cost implications of such countermeasures should be appropriately reflected in the bill of quantities

2.4.6.2 Considerations for Quality Control During Construction

Construction management personnel must fully understand the variability and behavior of laterite in both subgrade and fill applications. The following measures should be observed:

- Recognition of Laterite Variability:
  Laterite exhibits heterogeneous behavior depending on its depositional environment, depth, degree of weathering, and mineral composition. Therefore, real-time observation and adaptability in material handling are crucial.
- Compaction Control:
  Since compaction characteristics vary with moisture content and method, the compaction procedure established during laboratory testing must be carefully replicated in the field. Particular attention should be paid to:
  - Moisture conditioning before compaction
  - Ensuring uniform compaction energy
  - Frequent verification of field density and moisture content
- Initial Phase Control:
  Early-stage construction should be monitored closely to ensure the achieved compaction and strength are in line with design expectations. If discrepancies arise, prompt feedback should be provided, and adjustments made to the construction method.

2.4.7 Actions to Be Taken at the Maintenance and Management Stage

In areas where laterite is distributed, appropriate maintenance and management activities must be implemented to ensure that constructed facilities continue to perform as intended. Given that laterite exhibits high variability and potential changes in its properties over time, the maintenance of lateritic ground and facilities constructed with laterite materials requires routine inspections and proper documentation.

If signs of structural deformation (e.g., cracking, rutting, surface depression) are observed, prompt corrective actions should be undertaken to control the extent of damage and maintain the long-term performance of the infrastructure. All inspections and maintenance works should be conducted with reference to records from investigation, design, and construction stages.

[Explanation]

2.4.7.1 Maintenance Objectives

The primary objectives of maintenance are:

- To ensure that structures such as roads, canals, buildings, and embankments sustain their functional performance over time.
- To preserve structural safety by identifying early signs of failure and taking appropriate remedial actions.

In regions where laterite is present, cases of early pavement deterioration have been observed. Therefore, early detection of surface distress or underlying structural issues is crucial to avoiding major repairs and to maintaining serviceability.

2.4.7.2 Key Considerations for Maintenance

Laterite, either as a foundation material or as fill, can vary significantly in quality across a project site. This variability may result in:

- Localized pavement damage, such as cracking or rutting,
- Differential settlement, or
- Surface instability, especially in response to water infiltration or traffic loads.

If such signs are observed during routine maintenance inspections, engineers should:

- Review geotechnical data and design records from earlier phases,
- Determine the probable cause of the deformation (e.g., poor compaction, water ingress),
- And plan targeted remedial measures (e.g., sealing, localized replacement, or surface strengthening).

2.4.7.3 Inspection and Survey Protocols

Inspections are carried out to detect early-stage deformations that could progress into significant structural failures. Key considerations include:

- Prioritization of inspection zones: Based on past performance and areas known to have lateritic subgrades.
- Understanding the laterite-related failure mechanisms: Inspectors should be trained in identifying issues specific to lateritic soils (e.g., rutting due to water-sensitive fine-grained laterite).
- Visual and instrumented monitoring: Routine pavement evaluations should include checks for longitudinal cracks, transverse deformation, and rut formation.

In the context of Official Development Assistance (ODA) projects, it is essential to:

- Summarize required inspection and monitoring tasks to be transferred to local operators at project handover,
- Clearly define maintenance standards and reporting obligations,
- And ensure knowledge transfer on laterite-specific risks and maintenance strategies.

CHAPTER 3. OTHER PROBLEM SOILS

This section provides an overview of problem soils other than those listed in Chapter 2, mainly for the purpose of raising awareness. For information on the distribution area of problem soils, identification method and countermeasures, refer to the report "Basic research (project research) on countermeasures for problem soils encountered in construction work in developing countries around the world and reinforcement measures for local natural ground materials."

Problem soils covered in this chapter are as follows:

Mechanical properties	Erodible soil, crushable soil, soluble soil, soft soil (peat is the focus here)
Chemical properties	Saline soils, sulfate/sulfide soils, carbonate soils, acid soils
others	Coral soil, mica-rich soil, glacial soil, weathered rocks and metamorphic rocks, dry soil

3.1 ERODIBLE SOIL

Erodible soils refer to ground composed of geological materials that are easily deformed or displaced due to natural weathering and erosion processes. These grounds are susceptible to erosion by agents such as wind, water, ice, and gravity, leading to potential stability issues. Erodible soils present significant challenges across various sectors, including agriculture, construction, and environmental conservation.

[Explanation]

Erodible soils are sandy soils and sandy silts that have weak interparticle cohesion and have the following main characteristics:

Fragility: Erodible soils are very vulnerable to external forces and are easily eroded.

High permeability: Water easily penetrates into the ground, so it is easily washed away

Low cohesion: The bonds between soil particles are weak and the structure is unstable.

High weathering rate: Weathering is rapid, hence soil and rocks break down quickly.

Dispersible soil and collapsible soil are especially vulnerable to erosion. Depending on the clay minerals they contain and the strength of their cohesion, salt soil, carbonate soil, and sulfate soil are also susceptible to erosion. Soluble soil exists in the sense that it dissolves in water; however, it takes longer in geological time to dissolve than the above, so it is different from erodible soil.

Soil erosion and subsequent desertification are geotechnical disasters. Recent projections suggest that climate change could lead to a 30-66% increase in water-induced soil erosion worldwide between 2015 and 2070. The United Nations has expressed concern that the accelerating loss of arable land is contributing to global warming as it reduces the amount of carbon dioxide absorbed by soils. In response, various efforts are being undertaken to reduce soil erosion, including strengthening soil nutrients, water balances and reforestation.

Source: EUR 25402 EN‐Soil Atlas of Latin American and the Caribbean, Gardi, C., Angelini, M., Barceló, S., Comerma , J., Cruz Gaistardo et al., 2015

Figure 3.1.1 Example of gully erosion

Erodible soils present challenges in various locations, including collapse of slopes, the erosion of embankments, the collapse of slopes where vegetation has been reduced, the erosion of riverbanks, and the loss of land due to coastal erosion. This is especially critical in areas around houses and roads.

Source: A review on Problem Soils in South Africa, S. Diop, F. Stapelberg , K. Tegegn, S. Ngubelanga, L. Heath, 2011

Figure 3.1.2 Erosion of embankment due to erodible soil

Source: A review on Problem Soils in South Africa, S. Diop, F. Stapelberg , K. Tegegn, S. Ngubelanga, L. Heath, 2011

Figure 3.1.3 Erosion of erodible soil

3.2 CRUSHABLE SOIL

Crushable soils are defined as soils composed of brittle soil particles. When subjected to external forces, these particles break, resulting in deformation such as settlement. Examples of crushable soils include:

- Marine deposits such as calcareous sands and coral gravelly soils
- Volcanic deposits such as pumice and scoria
- Weathered residual soils such as decomposed granite (masado)

Depending on the magnitude of the external forces, ground materials may experience particle crushing. Therefore, it is essential to establish an index representing the degree of crushability and to compare this index with the magnitude of external forces encountered. This approach is crucial when incorporating the effects of particle crushing into geotechnical engineering considerations.

[Explanation]

(1) Calcareous Sand

Calcareous sands are found mainly in coastal areas and continental shelves in tropical and subtropical regions (e.g., Arabian Gulf, Gulf of Mexico, Northwest Shelf offshore Australia). The warm environment allows biogenic and biochemical processes to occur, producing calcareous sand deposits that are dominated by skeletal remains of marine organisms with a variety of particle types with different properties and shapes, as shown in Figure 3.2.1. Calcareous sands usually have a high calcium carbonate content, such as calcite and aragonite [$CaCO_3$], and also contain dolomite [$CaMg(CO_3)_2$], with variable content in both cemented and non-cemented conditions. The combination of high porosity and intergranular porosity makes calcareous sands highly compressible and susceptible to fracture at relatively low stresses.

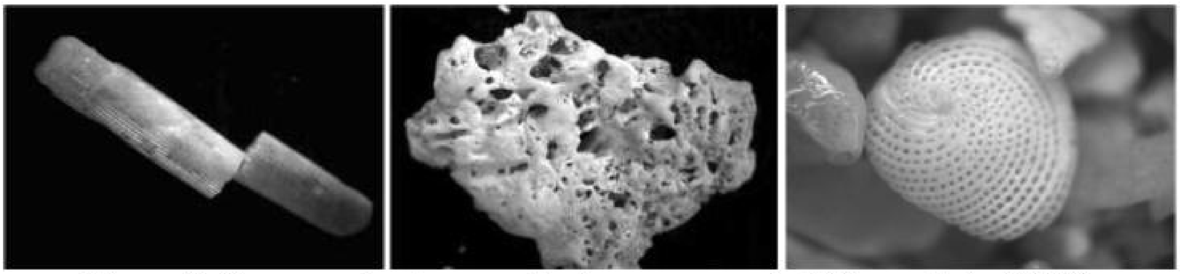


Figure 2. Some grain shapes of calcareous sands (Olgun et al., 2009)

Source: Sand compressibility aspects related to CPT, SM Ahmed, SW Agaiby , PW Mayne(2014)

Figure 3.2.1 Particle shape of calcareous sand

(2) Pumice

Pumice is a distinctive material that is typically fromed during explosive volcanic eruptions. The microscopic structure is explained by specific geological features such as magma flow (rhyolitic, andesitic, trachytic), deposition (fall flows and pyroclastic density flows), and type of volcanic material (tuff and pyroclastic flows). Due to its widespread mobility, pumice deposits are frequently encountered in construction work. Pumice is characterized by its light weight, easy crushing, angularity, cellular nature with high water absorption capacity, high surface roughness, large friction angle, and low compressive strength.

Scoria and Pumice

Both scoria and pumice are porous volcanic rocks; however, they differ in several aspects as outlined below. Although both can be categorized as crushable soils, pumice generally presents more serious engineering challenges due to its lower strength.

Characteristic	Scoria	Pumice
Color	Black, red, brown	White, gray, pale yellow
Density	Heavy (Specific gravity > 1.0) → Sinks in water	Light (Specific gravity < 1.0) → Floats on water
Vesicle (bubble) size	Larger vesicles (thick bubble walls)	Smaller vesicles (thin bubble walls)
Composition	Basalt to andesite (SiO_2 45–55%)	Rhyolite to dacite (SiO_2 65–75%)
Formation temperature	1000–1200°C (high-temperature)	600–900°C (low-temperature)
Eruption type	Lava flows, Strombolian eruptions	Explosive eruptions, Plinian eruptions
Mohs hardness	5–6	4–6
Compressive strength	10–50 MPa	1–10 MPa
Brittleness	Relatively tough (thick bubble walls)	Extremely brittle (thin bubble walls)
Crushability by hand	Difficult to crush	Easily crushed by hand

Source: JICA Study Team

(3) Weathered Residual Soil

Residual soil is defined as soil that has undergone weathering, resulting in the loss of its parent rock structure. Many countries also include colluvial soil in the category of residual soil. Weathered residual soil, a byproduct of rock weathering, is significantly influenced by the geological characteristics and weathering degree of the parent rock. It may contain soil similar to soft rock or reconsolidated soil, such as laterite. In that sense, the definition of weathered residual soil is not strict worldwide, and the definition varies from country to country. Laterite is also classified as weathered residual soil. Research on weathered residual soil is being conducted in various fields including geology, soil science, and soil engineering. However, research from the perspective of geotechnical engineering is relatively new, and many points are still unknown.

Weathered residual soil presents a unique challenge due to its heterogeneity and variability. The impact of discontinuities such as joints and foreign materials present within these areas on the strength, deformation, and permeability of the soil shall be assessed. Old joints or cracks that have been altered by the action of hot water tend to have relatively thick, irregularly shaped clay in the joints, and often contain montmorillonite.

(4) Engineering Issues

Particle crushing is a critical issue that must be addressed in various contexts in the field of geotechnical engineering. For instance, it plays a role in the lateral friction of driven piles, the durability of railway ballast, and the settlement of rockfill dams. Pumice deposits are commonly found in volcanic regions, but they pose a significant engineering challenge due to the presence of highly friable and compressible particles in their matrix. These deposits exhibit complex soil properties and are associated with natural phenomena such as landslides and earthquakes. The skin friction of piles in calcareous sand is significantly lower than that of piles in quartz sand. Repeated cyclic displacements of approximately 2% of the pile diameter can significantly reduce skin friction. It is important to note that the bearing capacity of piles in crushable soils cannot be estimated using conventional classical soil engineering estimation formulas. It has been reported that the bearing capacity of piles in volcanic ash soils is lower than that of ordinary soils in Japan. Crushing cannot be evaluated by sieving alone; detailed observation of particle morphology under a microscope is required to fully understand the structure and behavior of crushable sands.

3.3 SOLUBLE SOIL

Soluble ground refers to soil or rock that dissolves when exposed to rainwater, river water, or groundwater, leading to phenomena such as ground subsidence and collapse due to the formation of underground cavities.
Examples of soluble ground, listed in descending order of solubility, include:

- Limestone (including dolomite and chalk)
- Gypsum (including anhydrite)
- Salt (rock salt)

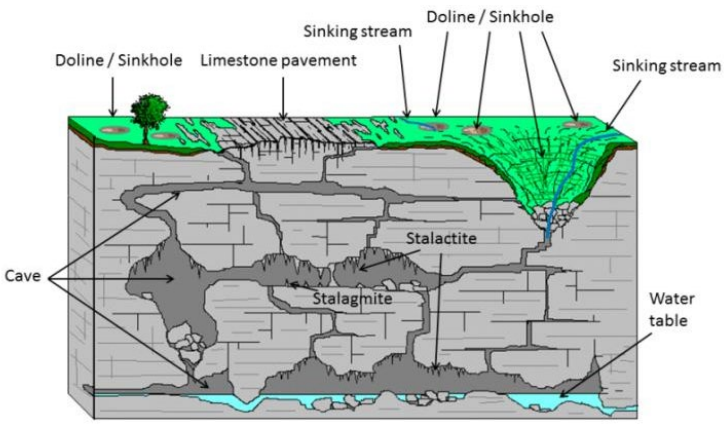
In general, construction in areas with karst topography poses significant risks of ground subsidence, making it challenging to establish structural foundations. Therefore, special attention must be given to planning and executing construction in these areas.

[Explanation]

(1) Features

Soluble soils, generally form underground cavities when exposed to rainwater, river water, or groundwater. These cavities are susceptible to collapse and subsidence. Soluble rock terrains are typically characterized by minimal surface moisture, with water channels flowing underground through solution-widened joints, cracks, strata, and caves. This process leads to the formation of distinctive landforms such as dry valleys and limestone pavements, collectively referred to as karst topography. Karst terrains pose various degrees of geological hazards, ranging from slow subsidence to catastrophic collapse and the development of destructive sinkholes. A conceptual diagram of karst terrain is shown in Figure 3.3.1. Soil-filled karst terrains are susceptible to instability due to inundation, piping, and erosion, and sinkholes can form on a timescale ranging from hours to days. The dissolution of rocks is not typically rapid enough to cause immediate collapse of structures. For salt, 100% dissolution occurs over a design life of 50 to 100 years. However, this is not the case of gypsum. Limestone dissolves much slower, taking thousands of years to affect structures built on it.

Soluble ground dissolves at different rates depending on the type, and can have complex geological structures, which pose unique engineering problems depending on the topography and geological conditions. When building on soluble ground, it is essential to thoroughly understand the characteristics of the ground (i.e., its physical, mechanical, and chemical properties) and to ensure the accuracy of the investigation of the foundation ground.



Source: https://lotusarise.com/karst-landforms-upsc/

Figure 3.3.1 Schematic diagram of karst topography

(2) Engineering Issues

The engineering challenge posed by karst topography is that in pile foundations, the limestone can melt, leading to the formation of sinkholes This can result in the appearance of large depressions appear on the ground surface, potentially causing damage to structures. Additionally, caves formed by karst topography are subject to structural degradation over time, leading to the formation of hollow, porous structures. In some cases, piles placed on bedrock can suddenly fall into voids below, causing problems such as rendering bridge piers unusable. Given the depth of these cavities, measures taken to deal with them pose significant challenges.

Fig. 10. The large dropout sinkhole in the suburbs of Guatemala City.

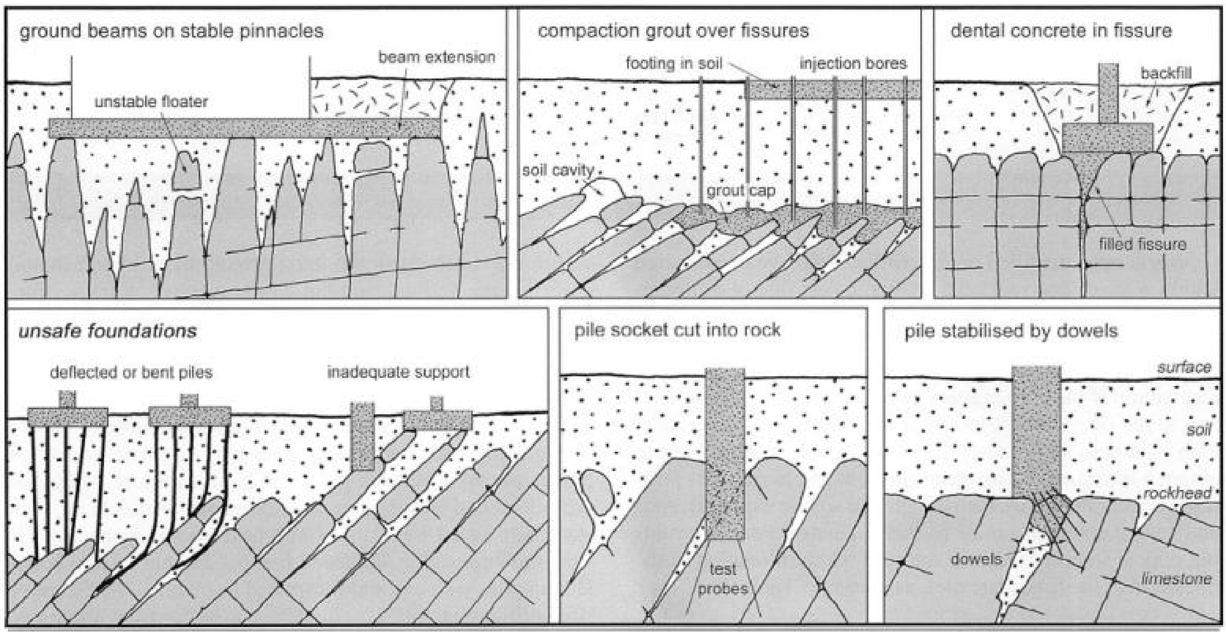
Source: Sinkhole hazard case histories in karst terrains, T. Waltham , 2008

Figure 3.3.2 Huge sinkhole

Fig. 12. The failed expressway viaduct after its pier had dropped into a void in the limestone beneath Tampa (photo: S. O'Rourke).

Source: Sinkhole hazard case histories in karst terrains, T. Waltham , 2008

Figure 3.3.3 Case of highway bridge pier falling into cavity



Source: ICE Manual of Geotechnical Engineering 2nd Edition Volume 1 Geotechnical engineering principles, problematic soils and investigation, Michael Brown , John Burland , Tim Chapman , Kelvin Higgins , Hilary Skinner , David Toll , 2024

Figure 3.3.4 Foundation work on limestone karst covered with soil

3.4 SALINE SOIL

Saline soils can be classified into three types: saline soils, saline-sodic soils, and sodic soils.
In saline soils and saline-sodic soils, high concentrations of salts can lead to structural corrosion and significant reduction in infrastructure lifespan.
Meanwhile, sodic soils exhibit dispersive behavior, where fine soil particles clog soil pores, impede water infiltration, deteriorate drainage, and reduce the overall permeability of the ground.
Therefore, during construction on such soils, appropriate countermeasures are necessary, including the removal of saline soils and the application of chemical treatments to improve soil drainage characteristics.

[Explanation]

Saline soils are defined as soils with high concentration of soluble salts and a low level of exchangeable Na+. Sodic (sodium) soils are defined as those with low level of soluble salt and high level of exchangeable Na+. Saline-sodic soils are soils that have a high concentration of both soluble salts and exchangeable Na+. The main characteristics of saline and sodic soils are shown in Table 3.4.1.

These soils are primarily found in arid and semi-arid regions where the ratio of precipitation to evapotranspiration is arid. These issues occur in coastal areas due to seawater inundations, in irrigated areas due to rising groundwater levels, and in some impermeable soils in humid areas due to lack of leaching.

In saline soils, the chemical properties of high salinity can corrode buried metal structures and pipelines, reducing the lifespan of infrastructure. When salt in saline soils penetrates concrete, it deteriorates the concrete through alkali-silica reaction and salt damage, potentially reducing the strength of structures and necessitating repairs. Due to the non-uniform soil formation and uneven salt distribution, the deformation characteristics vary, resulting in uneven settlement of building foundations. Saline soils tend to absorb water and can exhibit swelling characteristics, which can lead to issues similar to those caused by expansive soils.

Soda soils have a dispersive nature, meaning that when the soil disperses, the fine soil particles clog the gaps, preventing water infiltration and causing poor drainage, which in turn affects the ground's ability to drain properly. Dispersion of soil weakens the binding force between particles, reducing the stability of the ground and increasing the risk of landslides. This can lead to a reduction in compressive and shear strength, potentially causing issues in foundation work and road construction. Insufficient ground strength is a serious problem, especially under heavy structures. Dispersed soils are susceptible to erosion by wind and water, which can lead to loss of vegetation and changes in the topography. Soda soils are a type of dispersive soil, meaning they share the same characteristics and issues as other dispersive soils.

Table 3.4.1 Main characteristics of saline and sodic soils

Features	Saline soil	Sodic soil
Chemical	A neutral salt composed of chlorides and sulfates of sodium, calcium, and magnesium. pH<8.2, ECe>4dS/m. There is no clear relationship between pH and ESP. Soils may contain large amounts of sparingly soluble calcium compounds such as gypsum.	Neutral salts do not generally exist. Salts that are capable of alkaline hydrolysis, e.g., Na2CO3, do exist. pH>8.2, ESP>15, ESP<4 dS/m. pH and ESP are related. The predominant soluble cation is sodium. Soil pH causes soluble calcium and magnesium to precipitate, resulting in very low concentrations in the soil solution. There is almost no gypsum.
Physical	In the presence of excess soluble salts, the clay flocculates and the soil has good structure. The soil water and air permeability are good.	Excessive exchangeable sodium causes clay to disperse and soil structure to deteriorate. The permeability of soil water and air space is poor.
For plant growth Impact	Salt content in soils has negative effects on plant growth: Excessive salts affect the osmotic pressure of the soil solution, reducing water availability. The toxicity of certain ions such as Na, Cl, and B is influential.	Soda soils have a negative effect on plant growth: The dispersing effect of excess exchangeable sodium leads to poor physical properties; High soil pH contributes to nutrient imbalances, including calcium deficiency. For example, certain ions. The toxicity of certain ions such as Na, CO3, and Mo is a factor
Soil improvement	Remediation of saline soils essentially involves removing soluble salts from the root zone by leaching and drainage.	Chemical amendments must be followed by leaching, irrigation and drainage.

Source: Management of Soil Problems, Khan Towhid Osman(2018)

Figure 2: Capillary Rise in Water-logged Area, growing unhygienic living conditions (Sultanpur District)

Source: Engineering Problems in Sodic Soils and its Feasible Measures - A Pilot Study in Sultanpur District, Uttar Pradesh (2015)

Figure 3.4.1 Damage to earthen walls caused by capillary action in sodium soil

(1) Sabkha

1) Definition and Distribution

A sabkha is defined as a supratidal mudflat or saline sand plain. This flat saline landform is found in arid and semi-arid coastal or inland areas.

Its distribution is typified by the United Arab Emirates and the southern coast of the Persian Gulf, but it also appears in the geological record in the Mediterranean, Great Britain, Ireland and elsewhere.

Synonyms include Sebkha, salt flat and coastal/inland sabkha.

2) Origin and Process of Formation

The formation of sabkha is driven by three primary factors: a shallow marine carbonate environment, strong evaporation, and the capillary rise of groundwater. Evaporation causes the precipitation of halite minerals (gypsum, aragonite, anhydrite, etc.) from the surface to the shallow layers. The interaction between wet-dry cycles, groundwater, and aeolian deposition creates a unique flat, salt-rich surface.

3) Climate Factors and Influences

The annual evaporation rate is a maximum of 124 cm (lagoon) and an average of 6 cm (sabkhas). The region experiences significant temperature variations between day and night as well as between seasons, with temperatures ranging from 0 to 50°C. The area is also known for its dry days and foggy nights. Climate change and storms (shamals) can cause seawater to penetrate up to 5 km inland. Changes in the microtopography and physical properties of the substrate are a common occurrence, including the diagenesis of halite and gypsum, and the formation of polygonal cracks.

4) Geotechnical Features

a) Physical and Chemical Properties

High salinity groundwater (up to 23% NaCl) has been shown to cause weak bonds between soil particles and high corrosiveness. The constituent minerals include calcite, dolomite, gypsum, anhydrite, halite, and magnesite, among others. The high solubility of the binding minerals causes structural weakness and loss of bearing capacity.

b) Engineering Issues

- It has low strength and is highly non-uniform and prone to redeposits.
- The ground becomes weak due to cracks formed by drying and wetting, thermal expansion and contraction.
- Settlement, collapse, corrosive damage, and salt damage during construction and operation.

c) The impact of Groundwater

- The capillary rise zone has a significant impact on the surface layer and salt deposition due to evaporation, which can lead to soil degradation .
- The influence of the water table's slope on the land surface shape is directly proportional to the dominance of water and evaporation.

3.5 SULFATE/SULFIDIC SOIL

Sulfate soils are soils that contain a high concentration of sulfates (SO_4^{2-}). Representative sulfate compounds include:

- Calcium sulfate (gypsum: $CaSO_4 \cdot 2H_2O$),
- Magnesium sulfate (Epsom salt: $MgSO_4 \cdot 7H_2O$),
- Sodium sulfate (soda ash: Na_2SO_4),
- Iron sulfate ($FeSO_4$).

Sulfide soils are soils that contain a high concentration of sulfides (S^{2-}). Representative sulfide minerals include:

- Iron sulfide (pyrite: FeS_2),
- Zinc sulfide (ZnS), among others.

Sulfate attack can cause deterioration of concrete structures. Chemical changes in sulfur compounds associated with cement stabilization may induce expansive behavior. Careful consideration is required when dealing with sulfate or sulfide soils in civil engineering projects.

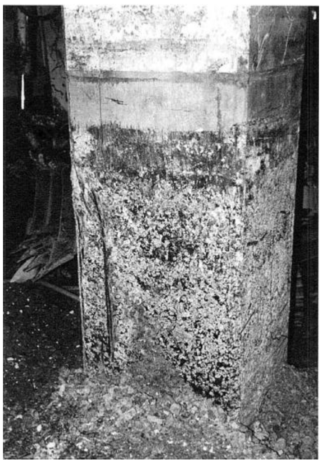
[Explanation]

Sulfur is common element in rocks and soils, existing in two primary forms: in its oxidized state as sulfate, mainly as gypsum ($CaSO_4 \cdot 2H_2O$), and in its reduced state as sulfide, mainly as pyrite (FeS_2). Other forms occur in special circumstances, such as gaseous hydrogen sulfide (H_2S) in landfills.

Pyrite (FeS_2) is the most common sulfide and is a common trace component of many igneous, metamorphic, and sedimentary rocks, as well as the soils derived from them. Sulfide minerals generally have very low solubility and do not pose a hazard to construction materials. However, the weathering of sulfides produces soluble sulfates (SO_4^{2-}), which can react chemically with natural and manufactured building materials. Under natural conditions, the weathering of sulfides typically results in the formation of gypsum ($CaSO_4 \cdot 2H_2O$), which has minimal solubility under neutral pH conditions and is the predominant form of sulfate in near-surface soils.

Sulfates occur naturally in evaporite sequences such as gypsum, anhydrite ($CaSO_4$), epsomite ($MgSO_4 \cdot 7H_2O$), and other salts. Barite ($BaSO_4$) occurs as a trace component in various types of rocks. Barite is extremely insoluble, whereas anhydrite, epsomite, and other salts are very soluble. As a result, they can be leached from near the surface where most civil engineering works are carried out and can only be encountered in unweathered rocks and soils at depth. In such conditions, they have the potential to cause significant problems for civil engineering works, such as corrosion and expansion of construction materials, especially when chlorides and other salts are also present.

The primary issues encountered in civil engineering projects are mainly associated with sulfates present in solutions and the transformation of one sulfur compound into another. Excavation can allow air and water to reach the sulfide minerals, leading to their oxidation to sulfate and the development of acidic conditions. This can result in the erosion of construction materials such as concrete and steel, heaving of embankments and overlying pavements, floor slabs, foundations, failure of artificial slopes and faces, clogging of drains and filters, and contamination of waterways. The treatment of sulfate- and sulfide-containing soils and rocks with lime or cement can lead to the formation of expansive sulfate minerals, which can result in heaving and the destruction of overlying construction materials. A common feature of many of these problems is that although some are manifested during construction, they do not occur immediately after construction but rather months or years after. These problems can be difficult and expensive to remediate, as they may require removal of the affected ground and embankments, and extensive repair or demolition of overlying structures. Examples of issues are shown in Figure 3.5.1 to Figure 3.5.4.

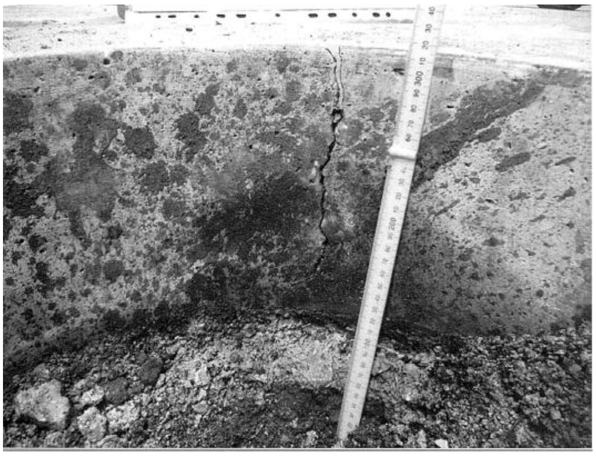


Source: ICE Manual of Geotechnical Engineering 2nd Edition Volume 1 Geotechnical engineering principles, problematic soils and investigation

Figure 3.5.1 Deterioration of reinforced concrete footings due to sulfate soil

Source: ICE Manual of Geotechnical Engineering 2nd Edition Volume 1 Geotechnical engineering principles , problematic soils and investigation

Figure 3.5.2 Corrosion of galvanized steel culverts on the A50 highway in the UK



Source: ICE Manual of Geotechnical Engineering 2nd Edition Volume 1 Geotechnical engineering principles , problematic soils and investigation

Figure 3.5.3 Cracking of engineered concrete slabs caused by sulfate-induced ground uplift

Source: Acid Sulfate Soils, Implications for Rural Landholders, Western Australia 2008

Figure 3.5.4 Cracking of engineered concrete slabs caused by sulfate-induced ground uplift.

3.6 CARBONATE SOIL

Carbonate soil is a type of soil that primarily contains carbonate minerals such as calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$).
Synonyms include lime soil, marl soil, and calcareous soil.

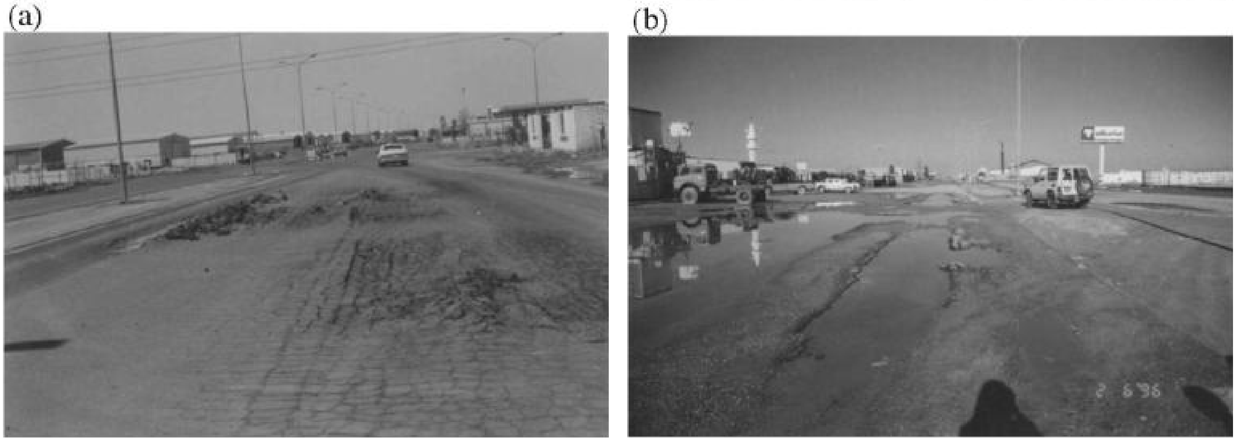
Carbonate soils are characterized by their uneven strength, posing risks of settlement and ground subsidence.
Although the underlying mechanisms differ, carbonate soils can exhibit behavior similar to expansive soils, potentially leading to cracking in the surfaces of roads, pavements, and structures.

[Explanation]

Carbonate soils are soils that contain carbonate minerals, mainly calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$). These soils are widespread, especially in arid and semi-arid regions. Synonyms include lime soil, marl soil, and calcareous soil. Depending on the weather conditions, they form at depths of 20 to 100 meters. Depending on the formation conditions, they range from hard rock, gravel, sand, clay, and silt to very fine and loose. Consequently, there is considerable uncertainty and variability in the characteristics of the soil. Those formed from weathered limestone and carbonate mineral particles have a relatively hard surface. Soils derived from coral reefs are also included in carbonate soils and become limestone over tims.. The primary source of carbonate soils is rocks containing calcium carbonate ($CaCO_3$), and the carbonates accumulate in the soil is a result of the process of weathering, dissolution, and precipitation of these rocks.

Rocks formed by the simultaneous deposition of calcareous material and clay are called marls. The formation of marls is the result of physical and chemical weathering of parent carbonate rocks such as limestone, dolomite, and carbonate sandstone.

The issues associated with carbonate soils are listed in Table 3.6.1.



(a) 3 months after construction (b) 2 years after construction

Source: Performance of a stabilized marl base a case study, SA Aiban , HI Al-Abdul Wahhab, OSB Al-Amoudi, HR Ahmed(1998)

Figure 3.6.1 Typical deterioration of a road based on marl

Table 3.6.1 Carbonate soil problems

Item	Problem
Road problems	Some marls have swelling properties and therefore pose the same problems of road deterioration as expansive soils.
Ground stability	Carbonate soils have uneven strength and are at risk of subsidence and sinking. Calcium carbonate is easily soluble in water, and when it reacts with rainwater or groundwater and dissolves, the ground can become unstable, causing the foundations of buildings and structures to sink, crack, and collapse.
Swelling	During the rainy season, $CaCO_3$ partially dissolves, widening the gaps between soil particles and causing the soil to expand in volume. Meanwhile, during the dry season, $CaCO_3$ reprecipitates and fills the spaces between the particles, causing the soil to shrink. In addition, carbonate soils may contain smectite, and soils with high concentrations of carbonates may become expansive due to the effects of Na^+ and Mg^{2+}. For these reasons, problems such as cracks can occur in roads, pavements, and structures, just like expansive soils.
Deterioration of structures due to chemical reactions	Carbonate soils are highly alkaline and therefore prone to chemical reactions with building materials such as concrete and rebar. Calcium carbonate reacts with the components of concrete to form ettringite, which can cause the concrete to expand and crack.
Marl road embankment material	Marl is sometimes used as road embankment material, but it can cause road subsidence and settlement, so when marl is used as an embankment material it is limed for economic and environmental reasons.

Source: JICA Study Team

(1) Marl

Marl is an earthy material or soft rock formed by the co-deposition of calcium carbonate ($CaCO_3$) and clay, which has the following characteristics:

- Parent rocks: physical and chemical weathering products of carbonate rocks such as limestone, dolomite, and claystone
- Ingredients: $CaCO_3$ (0-100%), clay, silt, sand, organic matter, etc.
- Condition: Wide range of soil conditions from unconsolidated to hard cemented soils
- A complex material that lies between geological and geotechnical classifications

Its characteristics are highly diverse, making it difficult to provide a uniform geological or engineering definition. The composition ratio ($CaCO_3$ / clay) significantly impacts strength and compressibility, and even at the same point, there is considerable variation in layer thickness and water content, complicating prediction of ground conditions.

Source: Marl crumbling decrease using geopolymer mixtures- lessons from experimental tests in the vicinity of Fez, Morocco, M. Akdim, L. Mesrar, A. Alami, S. Sabah, R. Jabrane, 2022

Figure 3.6.2 Marl starting to crumble

Marl is widely used as a construction material, but it is highly sensitive to water, resulting in a significant decrease in CBR value when wet. Its performance in roadbed construction under heavy loads and severe exposure conditions is questionable. Additionally, marl is susceptible to rapid strength loss due to repeated process of wetting and drying, causing roads to deteriorate when the optimum moisture content is not met, even at densities of 95% or more.

Depending on the clay minerals present, the soil may expand and swell when it absorbs water. Such marls are susceptible to developing large tension cracks, which can compromise slope stability on slopes with gradients of 10% or greater.

3.7 ACID SOIL

Acidic soil is defined as soil with a pH value less than 6.5.
Soil acidification is the result of a variety of natural and human-caused factors.
The primary sources of acids and hydrogen ions (H^+) in soils include:

- Atmospheric inputs such as acid rain,
- Weathering and alteration of minerals,
- Decomposition of organic matter accompanied by the release of CO_2 and organic acids,
- Microbial and root respiration,
- Root exudates,
- Release of H^+ ions through cation exchange processes, and
- Industrial and mining wastes, as well as fertilizer applications.

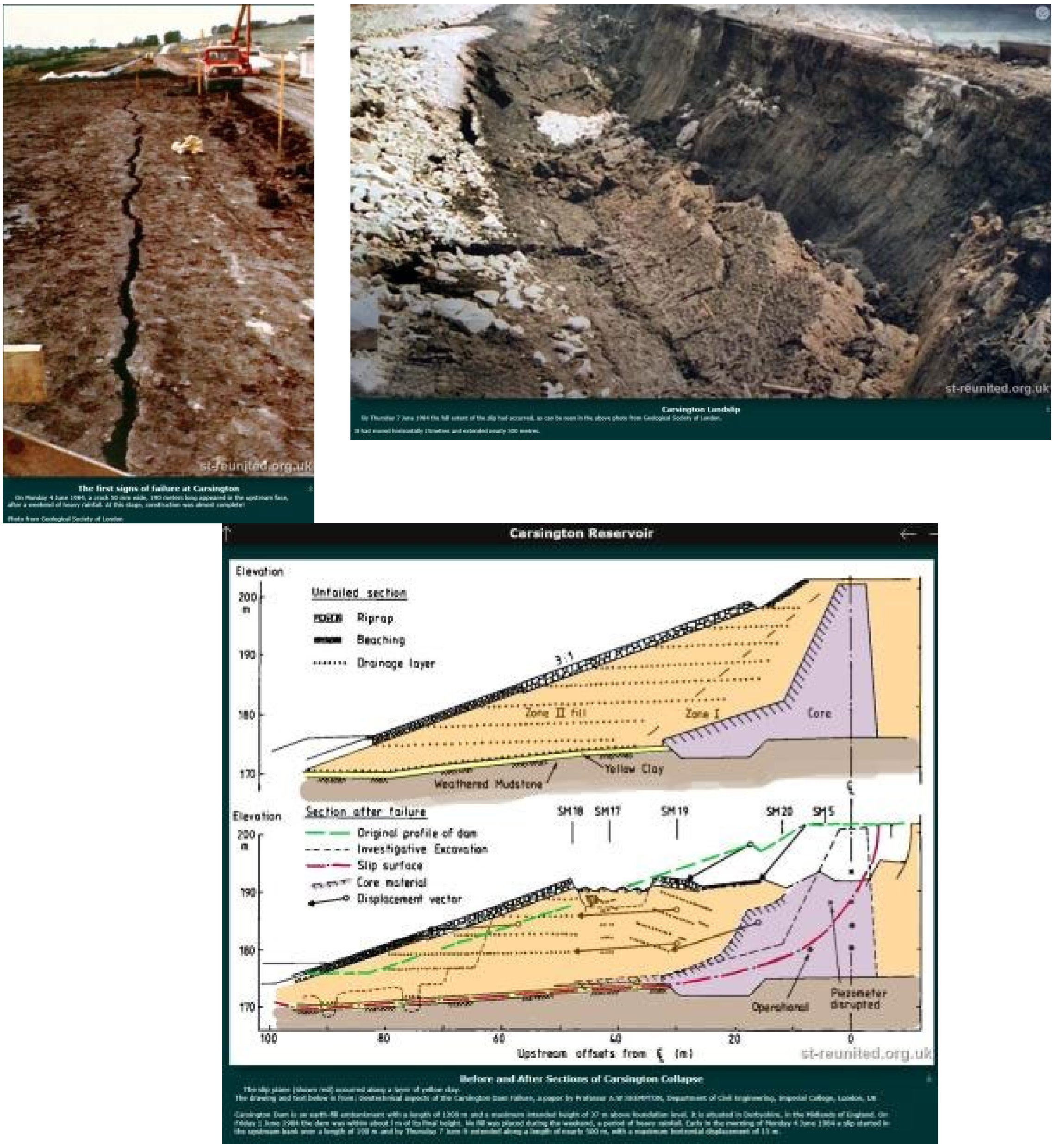
From an engineering perspective, acidic soils can corrode buried concrete structures, pipelines, and reinforced foundations, potentially reducing their lifespan.
Furthermore, under acidic conditions, heavy metals such as cadmium (Cd), lead (Pb), and zinc (Zn) are more likely to dissolve and leach from soils, potentially leading to groundwater and surface water contamination and causing serious environmental pollution.

[Explanation]

Soil is a very heterogeneous material, and its pH cannot be measured as accurately as a pure solution. Soil is said to be neutral if its pH is between 6.6 and 7.3. Soil pH generally ranges from 4 to 10. Good agricultural soils have a pH of around 6.0 to 7.0. Soils with a pH value below 6.5 are called acid soils.

Soil acidification is caused by a variety of natural and human-caused factors. Natural acid soils occur under a variety of conditions, including climate, parent material, soil, topography, and vegetation. Land use, soil and crop management practices are the main causes of anthropogenic soil acidification. However, the main sources of acid and hydrogen ions in soil are air and rainwater, mineral weathering and alteration, decomposition of organic matter with release of CO_2 and organic acids, microbial and root respiration, root secretions, release of H^+ in exchange for bases, industrial and mining wastes, fertilizers, etc. The processes of soil acidification include the production of organic and inorganic acids, exchange of H^+ with $Al3^+$ basic cations, and leaching of bases.

Acid soils are problematic in agriculture, but in engineering, acid sulfate soils are problematic due to their high acidity. Acid soils corrode buried concrete, pipelines, and rebar foundations, shortening the service life of structures. Heavy metals (e.g., cadmium, lead, zinc, etc.) are easily leached from the soil under acidic conditions, which can lead to water pollution by flowing into groundwater and rivers. At Carsington Dam (UK), the clayey acid sulfate soil left in the foundations during construction was oxidized by heavy rainfall, losing its strength and causing a slide and collapse (Figure 3.7.1).



Source: http://st-reunited.org.uk/History/Carsington/index.html

Figure 3.7.1 Carsington Dam slide failure

3.8 PEAT

Peat soil is a type of organic soil formed in wetlands and marshes through the accumulation and decomposition of plant remains and organic matter under waterlogged, oxygen-deficient conditions.
Its major distribution areas include the Arctic and subarctic regions, as well as tropical and temperate regions.

Peat is characterized by its high natural water content, low shear strength, and large void ratio. Due to these properties, significant settlement can occur when embankments are constructed on peat soils.
In some cases, settlement may be accompanied by slope failures of the embankment itself, requiring special attention in geotechnical design and construction.

[Explanation]

Peat is a type of organic soil that forms in wetlands and swamps. It is formed when plant remains, and organic matter are deposited and decomposed in water with limited oxygen. Peat is known to occur in the Arctic and subarctic regions but is also found in tropical and temperate wetlands. Peats in tropical regions form more slowly, and tree roots and trees may remain un-weathered, which can be an obstacle to excavation work.

Organic soils are classified based on their organic matter content. One of the organic soil types with the highest organic matter content is peat. Peat is composed of partially or completely decomposed plant remains, and organic matter accumulated in a water-saturated state (less than 25% of its weight in minerals). It has a spongy consistency, a distinctive organic odor, and is brown to black in color. Peat is recognized as a highly porous material with low shear strength and high compressibility, which is related to the peat's natural water content (over 200%) and very high organic matter content (over 75%).

The basic problems are the same as those of peat and organic soil in Japan. Peat generally has low undrained strength and high compressibility. Buildings on peat are usually supported on piles, but the surrounding ground still sinks, causing the drawn -in deformation shown in Figure 3.8.1. As shown in Figure 3.8.2, peat in tropical regions is formed late, and tree roots and trees may remain un-weathered, which may hinder construction work during excavation. Ground improvement work by mixing may also be difficult. In Kalimantan, irrigation channels were placed on peat to increase rice cultivation, but this caused the groundwater in the peat to drop, the peat to dry out, and wildfires naturally broke out (Figure 3.8.3) . The smoke rose into the sky, causing problems with aircraft operations. It is advised to be cautious since peat development not only destroys the natural environment but also causes problems such as CO_2 issues and operational problems for aircraft.

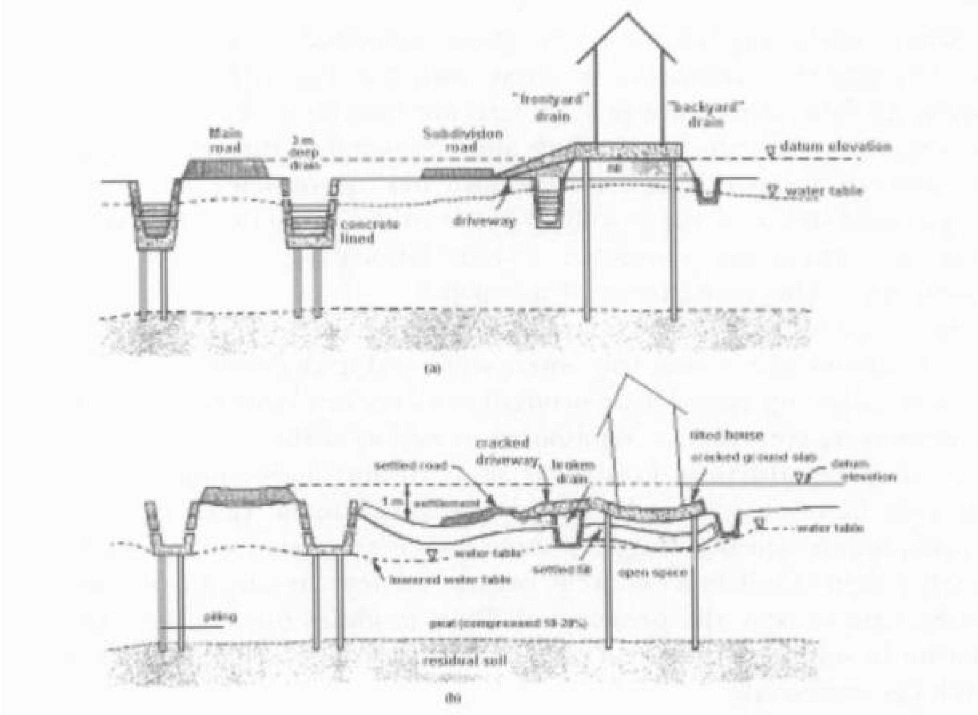


Fig. 1: (a) Typical section of a housing estate on peat (immediately after completion of construction) (b) Several years after completion of construction (scale exaggerated)

Source: Deformation and Shear Strength Characteristics of Some Tropical Peat and Organic Soils, Bujang BK Huat(2006)

Figure 3.8.1 Displacement of structures that have been treated by countermeasures due to subsidence of peat ground

Source: JICA Study Team

Figure 3.8.2 Peat in the wetlands of Kalimantan Island, Indonesia
(a large amount of un-weathered wood has been extracted from the soil excavated from a canal)

Source: https://forestsnews.cifor.org/49581/peatland-fire-policy-from-past-to-present?fnl=

Figure 3.8.3 Wildfire on Kalimantan Island, Indonesia

Regarding countermeasures against peat, the Manual for Countermeasures against Peat-Based Soft Ground can be used as a reference for the use of Japanese design methods. Other information can also be obtained from the same manual.

Table 3.8.1 Types of peat countermeasure methods

Construction method	Detailed name of construction method
Surface treatment method	Trench method
	Sand mat method
	Center drains method
	Laying material method
Replacement method	Excavation replacement method
	Forced replacement method
Reinforcement embankment method	
Embankment reinforcement method	
Slow construction method	
Loading method	Surcharge method
	Preloading method
Consolidation promotion method	Sand drain method
	Plastic drain method
	Vacuum consolidation method
Sand compaction method	
Consolidation method	Surface mixing method
	Middle mixing method
	Deep mixing method
	Lime pile method
	Gravel cement compaction method
Structural methods	Pile slab method
	Pile cap method
	Pile net method
Lightweight embankment method	Air-foam mixed lightweight embankment method
	Styrofoam block method
	Foam bead mixed lightweight embankment method

Source: "Manual for Countermeasures against Peaty Soft Ground" (March 2017, Public Works Research Institute/Civil Engineering Research Institute for Cold Region)

3.9 CORAL SOIL

Coral soils refer to soils derived from marine plants (coralline algae) and marine animals (corals). The calcareous strata formed by the accumulation of coral are known as coral reef rock.
As coral reef rock weathers and disintegrates over time, the resulting debris either remains isolated or mixes with other soil types to form coral soils.

Coral itself is highly porous, resulting in high water absorption capacity and relatively low density. However, with the passage of time, processes such as precipitation and recrystallization cause an increase in density, leading to the formation of rock-like materials with high strength and low porosity.

From a geotechnical engineering perspective, coral soils exhibit characteristics that are significantly different from typical cohesive or sandy soils.
Moreover, coral soils show considerable variability, particularly due to differences in coral content and coral type.
Because coral is inherently porous, when subjected to loading conditions such as during pile installation, the internal structure and cementation of the coral may collapse, preventing the soil from achieving the expected strength.
For these reasons, careful consideration must be given when dealing with coral soils in construction projects.

[Explanation]

Coral soil is classified as soil originating from coral, a type of calcareous deposit. It includes both coral gravel soil containing coral fragments as well as soil layers mainly composed of coral reefs and coral rocks. Coral generally has a porous structure, resulting in high porosity and high water absorption rate, as well as relatively low density. Over time, however, due to precipitation and recrystallization, coral becomes denser and stronger, forming coral reefs and coral rocks. Coral soil consists of coral, sand, silt, clay, etc.

Coral soil varies widely in terms of the coral content and the type of coral itself, making evaluation complicated from a geotechnical engineering perspective. For example, if the coral soil contains a small amount of coral gravel, the soil will be mainly composed of silt and other substances and will be prone to problems such as consolidation settlement. If the coral gravel content is high, the properties of the coral gravel will dominate the soil's behavior due to the interlocking of the coral gravel. In addition, because coral has a porous structure, unlike general gravelly soil, it is known that there are unknown aspects of its mechanical behavior, such as the destruction of the coral structure and cementation due to external forces such as the construction of driving piles, which can cause the specified bearing capacity to be lost and greater compression than expected.

When using coral soil as an aggregate, it is important to keep in mind that it has different characteristics from ordinary aggregates. Coral has a porous structure inside and has a high-water absorption rate, so moisture management of fresh concrete is important. It is also expected that air permeability will increase, which may affect long-term durability. On the other hand, because of its low density, it is expected to have the effect of reducing load.

There are currently no specific standards or manuals regarding coral soil. Currently, each country uses soil according to its own circumstances. In areas where soil mixed with coral gravel originating from volcanic islands, such as Palau (Koror Island and Babeldaob Island), the soil mixed with coral gravel is dredged from coastal borrow pits and used as general gravel soil, sandy soil, etc., as roadbed material or landfill material (see Figure 3.9.1) . In atoll areas such as the Marshall Islands (Majuro Atoll), coral rock is collected from coral reef quarries. Coral rocks are divided into dense layers (outside the atoll) and soft layers (inside the atoll: lagoon) depending on the location of collection (inside or outside the atoll). Dense layers are used as rubble and concrete aggregate, while the soft layers are used as roadbeds and fill materials (see Figure 3.9.2).

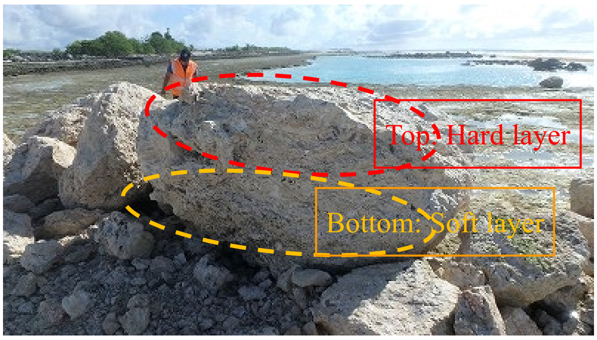
Coral gravel soil dredging site

Coral gravel soil

Source: JICA Study Team

Figure 3.9.1 Example of Coral Gravelly Soil (Palau)

Coral Rock Quarry



Coral Rock Quarry

Source: JICA Study Team

Figure 3.9.2 Example of Coral Rock (Marshall Islands)

3.10 MICA-RICH SAND

Mica is a group of silicate minerals characterized by a platy crystal structure.
When mica is present in significant quantities in sandy soils, the mechanical interlocking between the sand particles and the platy mica crystals results in distinct mechanical properties, such as bearing capacity and shear strength, that differ from those of ordinary sands.

In particular, during pile construction, there is a risk that the actual end bearing capacity obtained may be significantly lower than the estimated design value from the standard penetration test (SPT) N-value.
Therefore, special attention must be paid when applying conventional design formulas to micaceous sands.

[Explanation]

In some developing countries such as Bangladesh, cases have been confirmed in which the mechanical properties, such as bearing capacity and shear properties, of sand containing mica are lower than expected compared to normal sand. This is because mica is a layered silicate mineral with hexagonal plate-shaped crystals, and when it interlocks with the sand, it forms a special structure as shown in Figure 3.10.1 and Figure 3.10.2.

At pile construction sites in Bangladesh, the end bearing capacity of the piles was lower than the design bearing capacity based on the N-value, which caused issues.
The possible engineering problems associated with soil containing mica can be summarized as follows:

The presence of mica results in a smaller bearing capacity than that obtained with the classical bearing capacity formula. Both the tip and skin bearing capacity may be reduced.

Soils containing mica behave like destructive soils in shear (deform in compression during drainage shear).

The relative density and internal friction angle cannot be estimated from the N value.

When the amount of mica is large, the internal friction angle does not increase much regardless of the density. Also, the adhesive strength decreases as the amount of mica increases.

If mica content exceeds 10%, the compaction properties are reduced, and the material is highly compressible, resulting it becoming an unsuitable material for road paving, embankments, etc.

Repeated compaction leads to particle crushing, but at a certain number of compactions, particle crushing stops and the deformation characteristics stabilize.

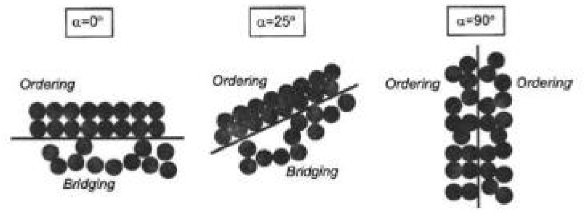
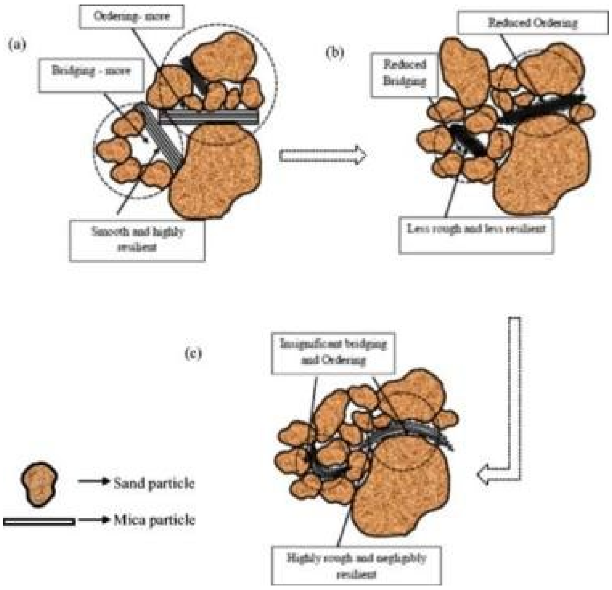


Fig. 1. Hypothesized bridging and ordering effects: Platy particle orientation α

Source: Micaceous Sands: Microscale Mechanisms and Macroscale Response, Lee JS, M. Guimaraes, JC Santamarina,, 2007

Figure 3.10.1 Special structure when sand contains mica



Source: Effect of Successive Impact Loading on Compactability, Microstructure, and Compressibility Behavior of Micaceous Sand , Seethalakshmi P. , Ajanta Sachan , 2018

Figure 3.10.2 Shear deformation when sand contains mica

3.11 GLACIAL DEPOSITS (GLACIAL SOILS)

Glacial deposits encompass a wide range of materials, from deformed basal layers that retain many of their original features to mixtures of gravel, sand, silt, and clay, and even to laminated clays. These deposits form either through pressure and shear action beneath advancing glaciers or by sedimentation during glacial melting.
Due to the diversity of depositional processes, glacial soils exhibit significant variations in physical and mechanical properties, and they are characterized by pronounced heterogeneity.
As a result, site investigations and laboratory testing are prone to producing considerable variability in the measured properties.

One notable problematic soil related to glacial deposits is quick clay.
Quick clay is widely found in regions formerly covered by glaciers, including Scandinavia, Canada, Russia, and Alaska. It is a highly unstable material with a high water content that can liquefy into a fluid mud-like consistency under minor disturbances.
Quick clay poses a significant geotechnical risk due to its potential to trigger large-scale landslides. Consequently, special attention must be given when planning and executing construction projects in areas where quick clay deposits are suspected or known to exist.

[Explanation]

Glacial deposits are one of the hazardous soils. These deposits are widespread in the cold regions of the world, accounting for approximately 10% of the total area. Although there is a large geological literature on Quaternary (glacial) geology, there is very little information on the geotechnical properties of these soils. Glacial deposits range from deformed basal layers that retain much of their original characteristics to mixtures of gravel, sand, silt, clay, and even thin clay layers. These deposits form under pressure and shear as a glacier advances or melts. Depending on the deposition mode, these soils vary spatially, which makes them difficult to classify and characterize. Inadequate geotechnical investigations and a lack of understanding of how depositional processes affect geotechnical behavior have led to claims and failures.

Normal sampling methods may not detect these characteristics due to sample disturbance. Sediments transported by glaciers and released as the ice mass retreats are called till. However, their properties cannot be explained by empirical theories, such as soil mechanics, which makes them difficult to handle. Till containing gravel or sand lenses may be difficult to sample due to variations in hardness, strength, and permeability depending on the depth. Gravel and cracks may also affect sample collection, leading to inconsistent test results.

Table 3.11.1 Scientific problems of glacial deposits

Step	Issues	Detail
Investigation	Strength	Some tills are too strong to obtain undisturbed samples. Till structure can have a significant effect on the strengths obtained from tests. Empirical correlations developed for stiff clays may not be applicable to basal tills. Drilling may not be positioned to pass through zones of weaker material.
	Permeability	Because of fractures and layering, permeability in the field is often greater than that measured in the laboratory.
	Boulder	The presence of a boulder may lead to it being mistaken for a bedrock head.
	Layered clay Laminated clay	It becomes difficult to distinguish between a lump of clay and a layer of layered clay.
	Sand and gravel	It is difficult to tell whether it is a pocket or layer of sand and gravel.
Drilling	Strength	Some glacial deposits, especially basal deposits, are very dense and therefore difficult to excavate, which is the reason explosives or road picks are used. Basal deposits may contain pockets of ductile soils, which can affect the stability of the excavation.
	Boulder	Glacial deposits may contain rocks of different sizes up to boulders, which can be problematic in excavating piles, tunnels, or diaphragm walls.
	Boulder beds	These may exist between different layers of till or between melted and basal till and will affect all forms of excavation.
	Layered clay Laminated clay	Deformed tills formed from glacial-lacustrine deposits may contain pockets, lenses or layered clay layers that may be softer than the surrounding till, leading to instability.
	Sand and gravel	Glaciolacustrine deposits and deformed deposits formed from them may contain pockets, lenses or layers of sand or gravel. They may contain water and cause water outbursts if connected to an aquifer or water source.
	Crack	Many basal sediments are fractured as a result of depositional processes, which can lead to block collapse and the formation of shear zones.
design	Strength	The in situ undrained shear strength of some basal sedimentary layers may exceed that measured in laboratory tests, potentially resulting in over-design.
	Hardness	The stiffness of some basal tills can cause settlement calculations to over-predict settlement, and pore water drainage can be slower than predicted.
	Boulder	Boulders pose an excavation problem, but the presence of boulders can cause test pile capacity estimates to be unconservative.
	Boulder Base	There is a possibility of uneven movement of the pile group supports at the ends.
	Layered clay	Pockets of layered clay can cause unequal movement of pile groups. Layered clay below the base of the pile can cause excessive settlement. Layered clay beyond the pile length can reduce bearing capacity. Layered clay layers can cause long-term slope failure.
	Sand and gravel	Clumps of sand or gravel may cause differences in the movement of the pile group.

Source: ICE Manual of Geotechnical Engineering 2nd Edition Volume 1 Geotechnical engineering principles, problematic soils and investigation, Michael Brown, John Burland et al(2024)

(1) Quick Clay

Quick clay is a special type of glacial soil. It is found in areas where glaciers once existed, including Northern Europe, Canada, Russia, and Alaska. It is very unstable and contains a lot of water; it turns into mud easily by shaking. The term "quick clay" refers to clays that collapse completely when remolded, resulting in a drop in shear strength to almost zero. Quick clays are defined as clays with a sensitivity ratio of 50 or higher and a fully remolded shear strength of less than 0.4 kPa. This value is determined by the penetration of a 60 g cone with a 60-degree tip angle of 20 mm fall in the fall cone test. The sensitivity ratio is the ratio of the undisturbed shear strength to the fully remolded undrained shear strength.

Quick clays are formed by slow geological processes. Most quick clays are formed in sediments that were deposited in seawater during the last glacial period. As the land rose after the inland ice retreated, leaving the clay deposits above sea level, leaching occurred, changing the ion concentrations in the pore water. Leaching is caused by the infiltration of rainwater, artesian pressure in underlying permeable soils or rocks, and diffusion. These processes are very slow, so quick clays are abundant in moderate-thickness clay deposits, less abundant in thick deposits, and only form in permeable layers and near the surface.

The principle of the formation of quick clay is summarized in Figure 3.11.1. Quick clay is often a predisposing factor for landslides in the region, so it must be taken into consideration during construction.

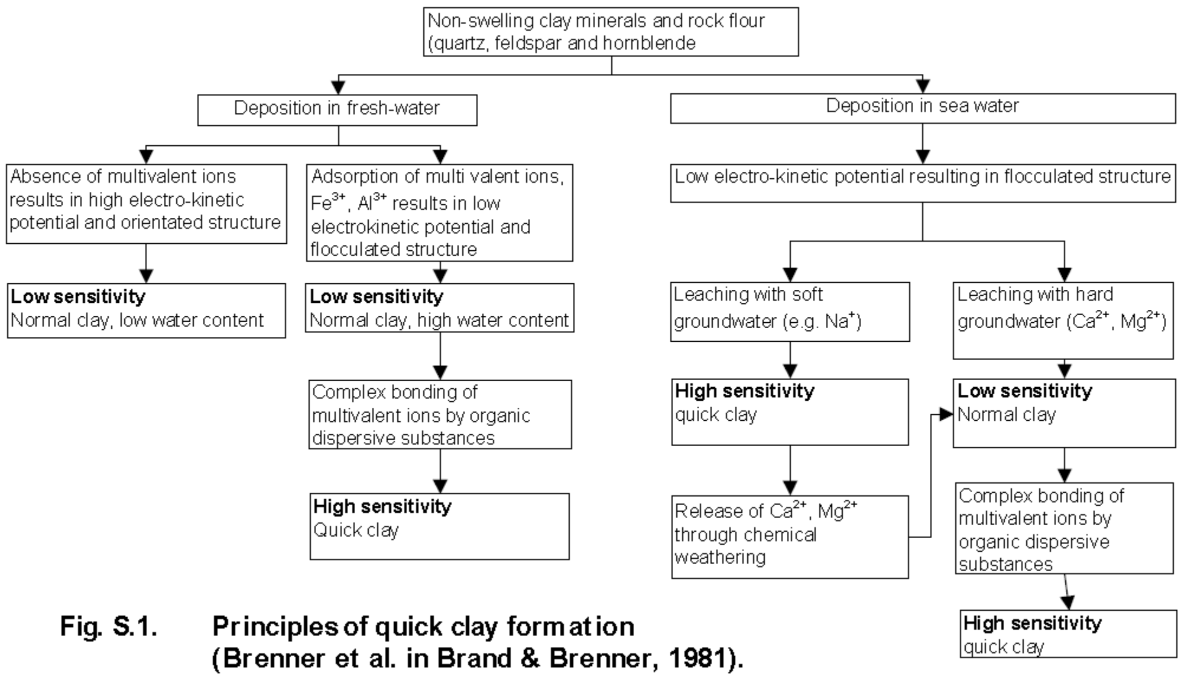


Fig. S.1. Principles of quick clay formation (Brenner et al. in Brand & Brenner, 1981).

Source: Quick clay in Sweden, KARIN RANKKA, YVONNE ANDERSSON-SKÖLD, CARINA HULTÉN, ROLF LARSSON, VIRGINIE LEROUX, TORLEIF DAHLIN(2004)

Figure 3.11.1 Principle of Quick Clay Formation

3.12 ARID SOIL

Arid soils refer to soils conditioned by arid climates, where the annual evaporation exceeds the annual precipitation, resulting in a persistent soil moisture deficit.

Due to their vulnerability to wind erosion, arid soils present significant challenges during construction activities.
For instance, sand and dust storms can severely reduce visibility at construction sites, leading to a decrease in operational efficiency.

Moreover, when using locally sourced water for construction purposes, there is a chance that it may contain high concentrations of dissolved salts, potentially affecting activities such as concrete production and curing.
Even if wells are drilled for construction water supply, insufficient groundwater availability may become a critical issue, impacting project execution.

[Explanation]

Arid soils are soils conditioned by an arid climate and result when annual evaporation exceeds annual precipitation, resulting in a lack of soil moisture. One-third of the Earth's land area is currently dry, and only about 25% of soil in extremely arid and arid regions consist of active sand dunes. Arid conditions are found in both hot and cold parts of the Earth, including hot desert soils such as the Sahara and cold desert soils such as the Gobi.

Dry soil types include Desert Soils, Regsols, Saline Soils, Alkaline Soils, Gypsiferous Soils, Calcisols, Solonetz Soils and Paleosols.

Dry soil, such as those in deserts, are vulnerable to wind erosion, and construction sites and roads can get covered in sand, reducing work efficiency and visibility. Limited water availability requires the use of locally sourced water, which may contain high levels of dissolved salts, affecting construction activities such as pouring concrete. Even when wells are drilled for construction work, groundwater supplies may be insufficient. Soils such as gypsum soils and Calxols (limestone soils) are hard and can be difficult to excavate and process, increasing construction costs and extending construction time. Alkaline and Solnetz soils exhibit swelling properties, causing the same problems as swelling soils.

3.13 WEATHERED ROCKS AND METAMORPHIC RROCKS

Certain weathered or metamorphic rocks can lead to problem soils through the process of pedogenesis. However, even before complete soil formation occurs, some of these rocks can pose significant geotechnical challenges. Rocks that undergo rapid weathering following excavation—such as during cut-and-fill operations—can lead to engineering issues due to changes in their mechanical behavior.

This section aims to provide a systematic overview of the relationship between the susceptibility of these rocks to weathering and the types of problematic soils that may result from their transformation.

Mudstone is a representative example of weathered rocks that warrant special attention. Depending on its mineralogical composition and internal structure, mudstone can exhibit a wide range of engineering behaviors. Therefore, careful evaluation of its characteristics is essential in geotechnical practice.

[Explanation]

How weathered rocks and metamorphosed rocks form into soil and how they become problematic is explained in the entries for each soil. However, some cause engineering problems before becoming soil, while others become problematic when they weather rapidly after being cut. Some rocks weather easily while others do not. Rocks with high alkalinity weather easily, resulting in various types of soil depending on the minerals they contain. Weathering also causes rocks to break down into various types of soil. The relationship between the ease with which rocks weather and the problem soils that result can be seen in Table 3.13.1.

Table 3.13.1 Various rock types and their weathering properties, and the Problem Soils that may form

Type		Weathered soil and problems	Weatherability	Acidity	Related Problem Soils
Plutonic rock	Granite	When weathered, it turns into decomposed granite, greatly reducing its strength. It is highly permeable, easily washed away by rainwater, and cut slopes are easily destroyed (highly erodible).	Weathering resistant	Acid	Masa soil
	Diorite	The soil type varies depending on the climate zone; laterite in tropical regions, clayey soil in temperate regions, and sandy soil in arid regions.	More susceptible to weathering than granite	neutral	(Laterite)
	Gabbro	It may turn into expansive soil due to its high content of expansive clay minerals.	Easily weathered	Basic	(Swelling soil)
	Peridotite	It easily reacts with water and oxygen and changes into serpentine or iron oxide (Fe_2O_3) (serpentinization).	Most susceptible to weathering	Ultra Basic	Swelling soil
Volcanic rock	Rhyolite	Clay soil	Weathering resistant	Acid	Laterite
	Andesite	It slaks and becomes clayey soil.	Easily weathered	neutral	Laterite
	Basalt	When weathered, it turns into clay and its strength decreases drastically. It produces highly swelling smectite (montmorillonite), turning it into	Very susceptible to weathering	Basic	Swelling soil Dispersible soil Laterite

Type		Weathered soil and problems	Weatherability	Acidity	Related Problem Soils
		expansive soil. As weathering progresses, it turns into laterite, a weak red soil.			
	Komachiite (Komatiite)	The soil becomes strongly alkaline and weak.	Most susceptible to weathering	Superbasic	
Metamorphic rocks	Greenschist (Greenschist)	Being a metamorphic rock derived from basalt, it will form a rooty soil, and there is a possibility that some of it will become swelling soil.	Very susceptible to weathering	Basic	Expansive soil?
	Amphibolite (Amphibolite)	Forms clayey soil.	Easily weathered	Basic	
	Gneiss	As sheet weathering progresses, it becomes more susceptible to peeling, increasing the risk of slope collapse. It is highly permeable, and if groundwater accumulates, it can cause collapse.	Weathering resistant	Acid	Laterite
	Marble	The soil becomes carbonate soil and alkaline soil.	Easily soluble in acid and easily weathered	Basic	
	Schist	The slope is sesceptible to collapse due to the developed lamination (layered cracks). When weathered, it causes slaking (collapse due to repeated wetting and drying), and its strength decreases rapidly.	Easily weathered	Acid from Basic	
	Slate	Rock formed by metamorphosis of shale and mudstone, and when it becomes soil it can cause similar problems.	Weathers easily (slaking)	Neutral to slightly Acid	
	Phyllite	Forms clayey soil.	Easily weathered	Neutral to slightly Acid	
	Schist	The slope is prone to collapse due to the developed lamination (layered cracks). When weathered, it causes slaking (collapse due to repeated wetting and drying), and its strength decreases rapidly.	Moderately weatherable	Neutral to acidic	
Sedimentary rocks	Chart	It does not form soil.	Very resistant to weathering	(Somewhat Acidic)	
	Quartz Sandstone	Long-term weathering can result in the formation of sandy soils .	Very resistant to weathering	(Somewhat Acidic)	
	Mudstone	It has high swelling properties and easily collapses when it absorbs water (contains montmorillonite). It is hard when dry, but when slaking occurs after absorbing water, it becomes crumbly.	Easily weathered	(neutral)	

Type		Weathered soil and problems	Weatherability	Acidity	Related Problem Soils
	Claystone	It has high swelling properties and easily collapses when it absorbs water (contains montmorillonite). It is hard when dry, but when slaking occurs after absorbing water, it becomes crumbly.	Easily weathered		
	Shale	Shale tends to collapse along the bedding lines. Clayshale slakes easily and forms expansive soil when it becomes clayey.	Very susceptible to weathering/slaking	(neutral)	Swelling soil Laterite
	Sandstone	Weathering forms weathered sand, which becomes granular soil. When it absorbs water, its strength drops rapidly. When sandstone is interbedded with mudstone, the weathering rates differ, making it unstable.	Relatively easy to weather	(neutral)	
	Limestone	Karst topography is easily formed, and underground cavities (sinkholes) are formed. It is easily dissolved by the influence of acid rain and groundwater. Unpredictable subsidence may occur.	Weathering resistant	(Basic)	Legosul
	Marl	When weathered, it becomes marl, a soil that exhibits swelling properties.	Very susceptible to weathering	(Basic)	Swelling soil
	Dolomite	Dolomite has a distinctive "elephant skin" texture that distinguishes it from limestone, and it can form carbonate soils.	Less susceptible to weathering than limestone	(Basic)	
	Ferruginous Mudstone	Weathering causes it to turn into clayey soil, but because it contains a lot of iron oxide, it can also turn into laterite.	Easily weathered	(Basic)	Laterite

Source: JICA Study Team

Some sedimentary rocks not only become problem soils, but also become moderately to strongly weathered rocks, which can cause problems when used as embankment materials. Mudstones are good materials for embankment, but if there are many voids between the soil particles, they may weather and cause settlement after embankment. It should also be noted that rainfall can accelerate weathering, causing settlement like collapsible soil.

Mudstone is the general name given to a variety of fine-grained, clay-rich sedimentary rocks. Mudstones frequently occur in sedimentary rock formations and are commonly found as natural foundations at construction sites. They may also be used as artificial foundations, fills, or construction materials. Depending on their composition and structural characteristics, mudstones can exhibit various engineering behaviors, some of which are problematic. These behaviors include low strength, poor durability, and susceptibility to volume changes. Mudstones typically range from soft, earth-like clay deposits to very stiff soils and medium-strength rocks, and are classified by uniaxial compressive strength as shown in Table 3.13.2.

Table 3.13.2 Classification of mudstone and soil based on strength

Classification by strength	Unconfined Compressive Strength	Features
Strong mudstone	50~100(MPa)	It can only be scratched with a knife or the tip of a geological hammer pick and can only be destroyed with multiple hard hits with a hammer.
Medium-strength mudstone	25~50(MPa)	It can be deeply scored with the tip of a knife or a geological hammer pick, and thin slabs may crack when pressed hard by hand. Specimens break easily with a single blow of a geological hammer or split with a knife blade. They cannot peel with a pocketknife.
Weak mudstone	5~25(MPa)	The tiny, gravel-sized pieces deform under hard finger pressure, are easily dented by a hard hit with the tip of a geological hammer and are difficult to remove with a pocketknife.
Very weak mudstone	1~5(MPa)	Hit hard with the tip of a geological hammer, and it will crumble and can be peeled off with a pocketknife.
Extremely weak mudstone	0.6~1(MPa)	A dent can be made in it with a thumb nail.
Extremely strong clay	300~600(kPa)	At the site, it was "very hard clay" - crumbling easily, unable to be remolded, and able to be indented with the nail of one's thumb.
Very strong clay	150~300	Determined by testing. "Very hard clay" at site.
Strong clay	75~150	Strong sticky clay
Medium clay	40~75	Field test determined it to be "hard clay" - it crumbles, breaks, and reforms into chunks.
Low clay	20~40	The on-site assessment was that it was "hard clay." It could not be molded but could be rolled into threads.
Very weak clay	10~20	The on-site assessment was that it was "soft clay." It could be shaped by lightly pressing with fingers.
Very weak clay	<10	The on-site assessment was "very soft clay." It was squeezed between the fingers.

Source: JICA Study Team

Examples of problems of mudstone is compiled for reference in Table 3.13.3.

Table 3.13.3 Problems on weathered rocks and metamorphic rocks

Cutting mudstone prone to slaking	In Indonesia, cut slope collapses have occurred during highway construction due to clay shale. Clay shale can easily be cut, even on steep slopes. However, slope collapses occur during the rainy season, which alternates with the dry season. The cutting of clay shale slopes causes many fine cracks. Thin clay forms in the slaking cracks, which then swell, expand the cracks, and form weak areas in the slope, leading to collapse. Although slaking occurs quickly, larger peeling does not occur compared to normal shale. Therefore, it is not immediately noticeable after cutting.
Basics	Mudstones tend to have insufficient bearing capacity for shallow foundations when closely spaced discontinuities or relatively weak bedrock are present. Despite the possibility of irrecoverable strains and nonlinear stress-strain relationships, it is common to use the modulus of elasticity as the deformation modulus. The anisotropy found in many mudstones can cause significant differential settlement, necessitating strong, reinforced concrete rafts or joints in the structure.
Volume change and deterioration of mudstone due to pyrite.	In pyrite-bearing mudstones, the oxidation of pyrite produces acidic pore waters that are rich in sulfates. Precipitation can occur outside the oxidation zone, especially in areas of least stress, such as bedding planes, joints, or structural interfaces. This occurs when expanding gypsum and other minerals form due to acid neutralization from reactions with calcite, concrete, and clay. Structural failure of buildings in northeastern England has been caused by expanding pyrite fill. Similar problems have occurred in mudstone bedrock in eastern Canada.
Drilling	The slaking characteristics of mudstones must be evaluated for the excavation of tunnels, shafts and other underground cavities. Mudstones with low silt and high clay contents may be strong enough to remain stable during excavation, but may deteriorate rapidly before the support provided by the lining can be fully achieved.
Expressway Construction	In highway construction, problems with pyrite-bearing mudstones can be mitigated by leaving the weathered material as it is as long as possible, or by covering the freshly exposed ground with a layer of compacted clay or a geomembrane barrier. An alternative is to expose the mudstone to weathering for a suitable period of time to allow oxidation of the pyrite and reaction products to form before construction. However, this construction plan can delay the schedule. Furthermore, the existing sulfates can contribute to chemical erosion and cause heaves due to dissolution and reprecipitation of sulfate minerals if surface and groundwater inflow is not properly controlled.
Settlement of high embankments using mudstone due to submersion	Mudstone is a sedimentary rock formed from the accumulation of fine particles such as silt and clay, which is easily affected by moisture. When used as a fill material, it can cause settlement due to water ingress. In addition, it is formed by densely packed fine particles, and has a relatively stable strength when dry. However, it can cause settlement due to water ingress. For example, if the mudstone fill material is coarse-grained, it will have many voids after construction. Even if the grain size is fine, the material will have many voids after compaction if the coarse and fine grains separate when it is spread out. If the material is sufficiently compacted in a dry state, meets quality control standards, and has sufficient surface strength, it is considered acceptable. However, when rain seeps in, slaking begins from the surface of large-grained mudstone. This weakens the contact points between the mudstones and causes soil particles to move into the voids. Deformation reaches the top of the fill, causing settlement. When using mudstone as a fill material, it is advisable to conduct repeated wet and dry tests to ensure the material's durability.

Source: JICA Study Team

CHAPTER 4. PROBLEM SOIL MEASURES

4.1 OVERVIEW OF COUNTERMEASURES

Countermeasure techniques for problem soils can be broadly classified into the following four categories: mechanical construction methods, chemical stabilization, biological stabilization, and other methods.

- Mechanical construction methods include:
  - Reuse of in-situ materials 4.1.1..2
  - Replacement methods
  - Surcharge or preloading techniques 4.1.1..3
  - Pre-wetting and ponding 4.1.1..4
  - Moisture control 4.1.1..5
  - Compaction methods 4.1.1..6
  - Cementation techniques
  - Reinforcement methods (e.g., using fill materials) 4.1.1..8
- Chemical stabilization encompasses both conventional techniques and methods that utilize industrial by-products or waste materials for soil improvement.
- Biological stabilization primarily involves the use of microorganisms, enzymes, and natural polymers.
- Other methods include electrochemical soil treatment and thermal treatment techniques.

Since countermeasure methods for problem soils are not yet fully established and existing knowledge remains limited, it is essential to carefully select appropriate techniques considering regional environmental conditions, geological and geomorphological settings, and construction constraints. Prior to full-scale implementation, trial construction should be conducted to assess both constructability and effectiveness.

In the construction and maintenance phases, ongoing monitoring of the effectiveness of countermeasures is critical. Even when the types of problem soils differ, similar countermeasures can often be applied. Therefore, it is important to select suitable countermeasures based on project requirements, local environmental and geological conditions, and site-specific constraints. However, as some methods remain unstandardized, thorough monitoring at all stages—investigation, planning, design, construction, and maintenance—is essential to ensure their effectiveness.

[Explanation]

When addressing problem soils, conventional design and construction techniques are often inadequate. It is therefore essential to adopt specialized countermeasure methods tailored to the specific geotechnical behavior of the soil. This section provides a general overview of countermeasure options to support the selection of appropriate remediation strategies. For detailed methodologies and practical implementation examples, readers are advised to refer to relevant technical literature and the case studies presented in the appendix.

As a reference for selecting suitable methods, Table 4.1.1 presents a matrix linking major types of problem soils with applicable countermeasure approaches. The table categorizes the measures by function—stabilization, moisture control, and strength improvement—and includes considerations such as effectiveness, practical application record, economic feasibility, and notes on implementation.

Methods that demonstrate both effectiveness and a successful track record are generally more reliable and widely adopted. Conversely, techniques with limited or no field application history, despite their theoretical efficacy, require thorough on-site validation before deployment. Even within the same soil classification, regional variability may affect applicability; hence, site-specific investigations, laboratory test, and pilot construction works are necessary to verify feasibility and performance.

Since standardized solutions for problem soils remain underdeveloped and empirical data is still limited, it is critical to select countermeasures that are suitable for the local environmental, geological, and topographical conditions, as well as project-specific constraints. Furthermore, it should be recognized that soils which appear stable during construction may pose future risks due to environmental changes or structural degradation. Therefore, continuous monitoring of countermeasure effectiveness during both the construction and maintenance phases is essential.

Table 4.1.1 Correspondence table of problem soil and countermeasures

Countermeasures				Applicable Targets	Expansive soils			Dispersive and Erosive soils			Colaapsible soils			Crushable spoils		Laterite
					Swelling, settlement, slippage			Erosion, sinking, piping			Erosion, settlement, bearing capacity			Settlement, bearing capacity		Soft soils
					Stabilization	Moisture Control	Strength	Stabilization	Moisture Control	Strength	Stabilization	Moisture Control	Strength	Stabilization	Strength	Strength
Mechanical treatment	In-situ reuse	High saturation construction managemen		In-situ material	△		×									
		In-situ mixing of good quality soil														
	Replacement	Good quality soil (sand, gravel)		acement ma	○A	×	○A	○A	×	○A	○1		○	○	○	○
		Recycled materials			▲A	×	▲A	▲A		▲A	▲1		▲	▲	▲	▲
		Filter Material							△							
		CNS Material			○	○										
		Stabilized soil			○	○	○	○	○	○	○	○	○	○	○	○
	Surcharge			Problem soils	△		△				△		△	△1	△1	
	Pre-wetting and Ponding				△		×	△		×	△		×			
	Moisture Control	Vegetation works		Eliminate problem factors		▽			▽			▽				
		Inflow water block				△			△			△				
		Drainage works				○			○			○				
		Horizontal and vertical barriers				○			○			○				
		Membrain				○			○			○				
		Spraying Work	Asphalt waterproofing			○			○			○				
			Concrete waterproofing			○			○			○				
		Filter							○							
	Compaction	Sand Compaction		Problem soils		××			××		○A		○A	○A	○A	●
		Gravel Compaction				××			××		○A		○A	○A	○A	●
		Vibroflotation				××			××		○A		○A	○A	○A	●
		Dynamic Comaction									△3		△3	△3	△3	●
	Consolidation	Soil Mixing	Surface mixing treatment	Problem soils	○	△	○	○	△	○	○		○			●
			Deep soil mixing					○H		○H	○4		○4	○4	○4	●
			High pressure injection					○H		○H	○		○	○	○	●
		Grout injection work						○		○	○		○	○	○	●
	Reinforcement (Embankment)	Geogrid,Geotextile		Embankment			○			○			○		○	○
		Geocompsite					○			○			○		○	○
		Geonet reinforcement					○			○			○		○	○
		Grocell Geogrid					○			○			○		○	○
Chemical Stabilization	Conventional Method	Cement (C) stabilization		Surface soil Replacement material Embankment material	○		○	○		○	○		○			○
		Lime (L) stabilization			○		○	○		○	○		○			●
		C+L stabilization			○		○	○		○	○		○			●
		C+F stabilization			○		○	○		○	○		○			●
	Challenging method	(C/L)+(cheap/waste) Stabilization	Dust		▲		▲	▲		▲	?		?	?	?	●
			Skag		△		△	▲		▲	?		?	?	?	●
			Silica fume		▲		▲	▲		▲	?		?	?	?	●
			Incineration ash		△		△	▲		▲	?		?	?	?	●
			Plant ash		△		△	?		?						
			Eggshell, seashell		△		△	?		?						
			Gypsum		▲		▲	▲		▲						▲
			Alum					△		△						
			Agricultural lime		▲		▲	△		△	▲		▲	▲	▲	●
			Water-based asphalt emulsion		▲		▲	△		△	▲	▲	▲			▲
			Calcium stabilizer		▲		▲	▲		▲	?		?	?	?	●
			polymer		△		△	△		△	▲	▲	▲	▲	▲	▲
			Soil Fiber		△		△	▲		▲	▲		▲	▲	▲	▲
		Asphalt Solvent						△		△	▲		▲	▲	▲	△
Biological Stabilization	Microorganisms			Surface soil Replacement & Embankment material Filling agent	●		▲	●		▲						▲
	Enzyme				●		▲	●		▲						▲
	Natural Polymers				●		▲	●		▲						▲
	Hybrid Method				●		▲	●		▲						▲
Classical Method	Electrochemical soil treatment			Problem soils	△											
	Heat Treatment				△											

Marks	Effect	Achievements	
○	Good	Yes	C: Cement
●	Good	No	L: Lime
△	Fairly good	Yes	F: Fly ash
▲	Fairly good	No	
▽	Better than nothing		
?	Possibility unknown		
×	Bad		
××	Counterproductive		
⊠	Unsolved		

Sufix

H Expensive/uneconomical

A Entire layer replaced/improved

1:Load distribution

2:Loading above crushing strength/design load

3:Less effective when the problem soil is deep

4:Not applicable when the problem soil is thick

5:Not suitable as embankment material

6:Possibility of material deterioration

Recycled materials	Recycled Crushed Stone
	Steel slag
	Coal ash (F)
	Sludge incineration ash
	Sewage sludge materials
	Tire chips
	Wood chips
	Glass Sand
	Recycled waste plastic
Dust	Cement clinker dust
	Lime clinker dust
	Slag dust

Biological Stabilization	Microorganisms	Bacteria
		Algae
		MICP
	Enzyme	Organic Enzymes
		Biopolymer Modification
	Natural Polymers	Guar Gum
		Chitosan
		Alginate
		Modified starch
		Acacia gum (Gum Arabic)
	Hybrid Method	Natural polymers x microorganisms
		Natural polymer x Enzyme
		Natural polymer x Soil fiber
Soil Fiber	Natural Fibers	Coconut fiber (coir)
		Rice straw and jute
		Fiber waste from plants and animals
	Synthetic	Polypropylene (PP)
		Polyester
		Nylon

MICP: Microbially Induced Calcium Carbonate Precipitation

Source: JICA Study Team

4.1.1 Mechanical Construction Methods

4.1.1.1 In-situ Material Reuse

The reuse of problem soil in-situ refers to the practice of retaining the native soil without removal and instead utilizing it as-is or subjecting it to mechanical improvement. This approach can reduce costs associated with disposal and transport, and also lower environmental impacts related to hauling operations. However, it necessitates advanced construction control and supplemental techniques tailored to the material properties.

(1) High Saturation Construction Management

High saturation construction management is a technique aimed at stabilizing the mechanical properties—particularly strength and deformation characteristics—of problem soils by properly managing the moisture content and degree of saturation during construction. It is especially effective for expansive soils and high-moisture-content soils.

This technique is applied when moisture reduction to optimal levels is difficult under field conditions. The construction objective is to align the moisture content and dry density as closely as possible to the zero-air-void line of the compaction curve, targeting near-100% saturation.

- For expansive soils, maintaining a moisture content above the optimum with high saturation suppresses swelling behavior.
- For collapsible soil, pre-wetting and compacting can mitigate volume change upon wetting.
- *Key Considerations*:
- Compaction densities may be less than 90%, potentially reducing shear strength.
- Achieving high density at elevated moisture contents is technically challenging; minimizing variability in field moisture and density is critical.

(2) In-situ Mixing with Good Quality Soil

This method improves overall engineering properties by directly mixing the problem native soil with good quality soil (e.g., sand, gravel). It falls under the category of physical and mechanical stabilization techniques. Compared to full soil replacement, this method requires less high-quality material.

The blending ratio should be optimized to both reduce the problem characteristics and enhance compaction behavior and workability. For expansive soils, increasing granular content reduces expansive potential. However, excessive addition can raise permeability, potentially reactivating the swelling of underlying residual soils. The mixture should be optimized to produce CNS (Cohesive Non-swelling Soil), suitable for replacement use.

4.1.1.2 Replacement Method

The replacement method involves partial or full excavation of problem soils and substitution with materials possessing suitable geotechnical properties.

- Offers high workability and reliable performance.
- Particularly effective where problem soils are shallow.
- Selection of replacement material is critical to the effectiveness of the measure.

Types of Replacement Materials:

(1) Good Quality Soil (Sand and Gravel)

- Exhibits excellent drainage, compaction, and mechanical strength.
- Ensures long-term stability of the ground.

(2) Recycled Materials

- Derived from processed construction debris such as excavated soil, asphalt millings, and crushed concrete.
- Environmentally friendly and promote material recycling.

(3) Filter Materials (Permeable Media)

- Engineered for high permeability and appropriate gradation to prevent migration of soil particles (e.g., include clean sand or gap-graded crushed stone).
- Primarily used as interlayers or protection layers, especially against piping and erosion in dispersive or erodible soils.

(4) CNS (Cohesive Non-swelling Soil)

- A specially selected clayey soil exhibiting cohesion without expansive behavior.
- Used to replace expansive clays or as a buffer layer.
- Controls expansion/contraction due to moisture fluctuations.
- It can be derived through stabilization of expansive soil.
- Widely applied beneath pavement subgrades, rail embankments, and building foundations.

(5) Stabilized Soil

- Soil is mechanically enhanced with stabilizers such as cement or lime to improve strength and deformation resistance.
- Aims to reduce problem behavior.
- Mixing and compaction can be performed on-site or at a centralized plant.

4.1.1.3 Surcharge / Loading Method

The surcharge method is a ground improvement technique that involves placing a temporary surcharge load atop the ground surface to induce excess pore water pressure, thereby accelerating drainage and consolidation of the underlying soils. While it is commonly employed to suppress long-term consolidation settlement in soft ground, its application extends to various types of problem soils.

- In expansive soils, the surcharge is applied to counteract the swelling pressure, effectively suppressing post-construction heave. This method is suitable when the soil exhibits moderate swelling potential.
- In collapsible soils and crushable soils, the surcharge is used to trigger settlement in advance, thereby minimizing unexpected deformation during service life.
- For collapsible soils, the method is often implemented in combination with pre-wetting, enhancing collapse prior to structural load application.

4.1.1.4 Pre-wetting and Ponding

Pre-wetting involves the deliberate addition of water to the ground or embankment material before the main construction phase, to control the moisture content and degree of saturation. One common technique is ponding, wherein water is retained on the ground surface in a controlled manner to allow deep infiltration over time.

- For expansive soils, pre-wetting induces initial swelling before construction, providing a swelling history. Subsequent compaction and structural placement are then conducted after the primary swelling has occurred, reducing the expansiveness of post-construction.
- Because expansive soils often exhibit extremely low permeability, ponding may take several years to achieve sufficient saturation at depth.
- Care must be taken to avoid excessive saturation, which can lead to loss of shear strength and transformation into muddy, unworkable material.
- For collapsible soil, pre-wetting and ponding are employed to intentionally initiate collapse prior to construction. However, care must be exercised to avoid unintended wetting during construction, which can result in unexpected settlement post-construction.

4.1.1.5 Moisture Control

Moisture control refers to geotechnical engineering techniques aimed at stabilizing problem soils by regulating moisture content and the infiltration/discharge of water. This is particularly applicable to expansive soils, dispersive soils, erodible soils, and collapsible soils.

Typical moisture control methods include:

- Drainage works: Removal of surface and subsurface water to stabilize moisture content.
- Inflow prevention structures: Barriers to block surface runoff from entering the soil.
- Vegetative protection: Use of vegetation to reduce raindrop impact and minimize surface infiltration.
- Filters: Granular or geosynthetic materials installed to prevent internal erosion while allowing water to escape.

Additional measures include waterproofing systems, such as:

- Horizontal/vertical impermeable barriers,
- Waterproof membranes (e.g., geosynthetic liners),
- Asphalt or concrete cut-off walls.

By effectively integrating these methods, risks such as ground deformation, swelling, erosion, and collapse can be significantly mitigated.

4.1.1.6 Compaction Method

Compaction is a ground improvement technique used to enhance the density, strength, and stability of problem soils such as collapsible soils, crushable soils, and laterite. The following are representative compaction methods:

(1) Sand Compaction Method

- Formation of sand columns to densify surrounding soils via lateral confinement and driving effects.
- Improves bearing capacity and drainage, particularly effective for collapsible soils and weathered laterite layers.

(2) Crushed Stone Compaction Method

- Vibration and impact are used to compact placed crushed stone, improving permeability, drainage, and load-bearing capacity.
- It is particularly effective for crushable soils, where it helps prevent bearing capacity loss.

(3) Vibroflotation Method

- A vibrating probe (vibroflot) is used in a saturated state to densify deep loose soils.
- Effective for pumice soils and weathered lateritic layers to improve deep soil structure and strength.

(4) Dynamic Compaction (Weight Drop Method)

- Heavy weights are dropped repeatedly to compact deeper layers, destroying weak initial structures.
- Stabilization is achieved through recompaction and reorganization of the soil matrix.

Precautions:

- In expansive soils, dispersive soils, and erodible soils, these methods may be counterproductive due to the potential for moisture attraction, leading to swelling, collapse, or particle dispersion.
- Sand compaction and vibroflotation require external water supply, making them unsuitable for moisture-sensitive soils.
- Dynamic compaction may cause particle crushing and slurry formation, especially in weak or fine-grained soils.
- For dispersive and erodible soils, post-construction drainage and surface protection (e.g., vegetation, filters) are critical to prevent erosion due to rainfall infiltration.

4.1.1.7 Solidification Method

The solidification method (also known as chemical consolidation) involves mixing cementitious or other stabilizing agents with problem soils to chemically bind and solidify the soil particles. This enhances both the strength and deformation resistance of the treated ground.

This method is widely used for the improvement of expansive soils, soft cohesive soils, collapsible soils, and crushable soils.

The types of solidification methods and their characteristics are summarized in Table 4.1.2.

Table 4.1.2 Types and Overview of Solidification Techniques

Technique		Description	Applicable Soils
Mixing Methods	Shallow Mixing Method	Soil up to several meters from the surface is mixed and compacted with stabilizers (e.g., cement, lime) using mechanical mixers, leading to solidification.	Applicable to road subgrades, embankments, and surface improvements. Particularly effective for shallow stabilization of collapsible and expansive soils.
	Deep Mixing Method	A vertical shaft is drilled into the ground, and stabilizers are injected and mixed in situ to form columnar improved bodies.	Effective for ensuring bearing capacity and suppressing settlement in soft ground, crushable soils, and volcanic ash-derived soils.
	High-Pressure Jet Grouting	High-pressure cement slurry is injected while simultaneously fracturing and mixing the soil, creating high-strength solidified columns.	Suitable even in heterogeneous soil layers and high groundwater conditions. Particularly used for improving laterite, volcanic crushable soils, and constructing impermeable walls.
Grouting Methods	Grouting Injection	Low-viscosity grout materials (cement-based or chemical) are injected into voids and fractures in the existing ground to solidify and reinforce the ground mass.	Enhances impermeability, bearing capacity, and overall integrity. Effective for collapsible soils, crushable volcanic soils (such as pumice deposits), and highly porous volcanic formations.

Source: JICA Study Team

4.1.1.8 Reinforcement Techniques (for Embankment Materials)

In problem soils such as soft ground, expansive soils, collapsible soils, and crushable soils, issues related to deformation, settlement, and reduced stability are significant concerns.

Reinforcement techniques utilizing geosynthetics are highly effective countermeasures.

Table 4.1.3 summarizes the types and basic characteristics of reinforcement techniques.

Table 4.1.3 Types and Overview of Reinforcement Techniques

Reinforcement Material	Description	Effect	Applications
Geogrid	High-strength polymer-based grid-like reinforcement laid within embankments or subgrade layers.	Controls lateral deformation and enhances shear strength and bearing capacity through tensile reinforcement.	Used for embankment reinforcement over expansive soils, soft ground, and crushable soils.
Geotextile	Nonwoven or woven fabrics providing filtration and reinforcement functions.	Effective for preventing particle intermixing, controlling drainage and infiltration, and separating foundation materials.	Applied to prevent internal erosion and stabilize ground in dispersive soils and erodible soils.
Geocomposite	Multifunctional materials combining geogrids, geotextiles, and drainage layers.	Integrates multiple functions such as reinforcement, drainage, and impermeability.	Effective for complex problem soils such as expansive and collapsible soils.
Geonet Reinforcement	Three-dimensional mesh-like materials offering both drainage and reinforcement capabilities.	Effective for steep embankment stabilization and infiltration water management.	It is used to mitigate softening of ground due to rainwater infiltration, particularly in collapsible soils.
Geocell Geogrid	Three-dimensional cellular (honeycomb-like) structures that confine embankment materials.	Provides load distribution, settlement mitigation, and erosion control.	Suitable for reinforcing pavements and road bases over soft ground, expansive soils, and erosion-prone soils.

Source: JICA Study Team

4.1.2 Chemical Stabilization

4.1.2.1 Conventional Construction Methods

Chemical stabilization refers to the process of mixing chemical stabilizers into the soil to enhance its strength, deformation resistance, and hydraulic performance through chemical reactions. This method is widely employed for the improvement of expansive soils, soft clays, collapsible soils, and dispersive soils.

Table 4.1.4 provides a classification and overview of the primary conventional chemical stabilization methods.

Table 4.1.4 Conventional Chemical Stabilization Methods

Stabilization Method	Overview	Applicable Soils	Key Features
Cement (C) Stabilization	Mixing with Portland cement to induce hydration reactions, leading to solidification and strength gain.	Effective for improving bearing capacity and reducing permeability of soft soils, dispersive soils, and collapsible soils.	Achieves high strength within a short period.
Lime (L) Stabilization	Using quicklime or hydrated lime to react with clay minerals, reducing swelling potential and plasticity.	Particularly effective for expansive soils (e.g., montmorillonitic clays).	Enhances workability through pH increase and particle flocculation; effective for initial soil improvement.
C+L Combined Stabilization (Cement + Lime)	Suppresses initial swelling and plasticity using lime, followed by strength gain through cement hydration.	Effective where single-agent treatment is insufficient, such as in expansive soils and high-moisture-content clays.	A stepwise stabilization mechanism that provides both immediate and long-term improvements.
C+F Stabilization (Cement + Industrial By-Products)	Combines cement with industrial by-products such as fly ash (F), utilizing pozzolanic reactions for soil improvement.	Applied for the stabilization of crushable soils, lateritic soils, and other local materials.	Contributes to environmental impact reduction and cost savings.

Source: JICA Study Team

4.1.2.2 Stabilization Using Waste Materials and By-products (Emerging Techniques)

In recent years, environmentally conscious soil stabilization techniques utilizing industrial by-products and waste-derived materials have garnered attention as sustainable alternatives to conventional stabilizers. These materials, which serve either as replacements or supplements to traditional binders like cement and lime, have shown potential in improving the strength, swelling characteristics, and permeability of problem soils.

It should be noted that the term “waste materials” herein refers to materials such as incineration ash from municipal solid waste and sewage sludge, plant ash, wood ash, and organic shell-derived materials (e.g., eggshells, mollusk shells), which differ from typical landfill-bound industrial waste.

The waste and by-products used for stabilization can be classified as follows:

(1) Inorganic By-products and Industrial Waste

- Dust and Sludge: e.g., Steel mill dust, steel sludge
- Slag: e.g., Ground Granulated Blast Furnace Slag (GGBFS), Electric Arc Furnace Slag (EAFS)
- Incineration Ash: e.g., Municipal Solid Waste Incineration (MSWI) ash, Sewage sludge ash
- Plant Ash and Wood Ash: Biomass combustion by-products with pozzolanic potential

(2) Organic and Naturally Derived Waste

- Eggshells and Mollusk Shells: Rich in Calcium Carbonate ($CaCO_3$); promote soil flocculation and stabilization
- Gypsum: Calcium Sulfate ($CaSO_4 \cdot 2H_2O$); effective for ion exchange in dispersive soils
- Alum: Aluminum Sulfate ($Al_2(SO_4)_3$); enhances flocculation and reduces dispersibility
- Agricultural Lime: Finely ground limestone used as a calcium source to stabilize expansive and dispersive soils

(3) Polymers, Fibers, and Chemically Treated Agents

- Polymers: Natural (e.g., polysaccharides, starch) or synthetic (e.g., polyacrylamides); improve cohesion and reduce erosion
- Soil Fibers: Reinforcement with natural (coir, jute) or synthetic (polypropylene, polyester) fibers to increase tensile resistance
- Asphalt-based Products: Solvents and emulsions used to enhance waterproofing and reduce soil permeability

These alternative stabilization materials should be evaluated through laboratory testing and field trials prior to full-scale implementation. Material suitability, dosage, mixing methods, and performance under site-specific conditions must be verified to ensure engineering efficacy and long-term durability.

4.1.3 Biological Stabilization

Biological stabilization refers to a method that utilizes microorganisms, enzymes, and naturally derived organic compounds (e.g., polymers) to bond and reinforce soil particles and regulate moisture content. This process serves to mitigate various geotechnical issues associated with problem soils, such as swelling, collapse, erosion, and subsidence. In recent years, it has garnered attention as an environmentally sustainable, low-carbon alternative in soil stabilization technologies. Table 4.1.5 presents the types and an overview of biological stabilization methods.

Table 4.1.5 Biological Stabilization Methods and Their Overview

Method	Principal Mechanism	Applicable Soils	Examples of Effects
Microbial Treatment	Induction of mineral precipitation to cement soil particles.	Crushable soils, collapsible soils, erodible soils.	Improved strength, reduced permeability.
Enzymatic Treatment	Enhancement of particle bonding through enzyme-catalyzed reactions.	Clayey soils, erodible soils.	Increased shear strength, enhanced erosion resistance.
Natural Polymer Application	Formation of physical coating and coagulation by natural polymers.	Expansive soils, dispersive soils, erodible soils.	Suppression of water absorption, improved soil stability.
Combined Biological Treatments	Synergistic and complementary use of multiple biological mechanisms.	Broad range of problem soils (complex ground conditions).	Multifunctionality, enhanced long-term stability.

Source: JICA Study Team

4.1.4 Other Construction Methods

These are construction methods historically employed in countries such as Russia and Ukraine. However, specific applications remain unclear, and little to no research has been conducted to validate their effectiveness. Consequently, their performance is not assured.

(1) Electrochemical Soil Treatment

- A method that stabilizes soil by applying an electric current to induce the migration of water and ions, resulting in dehydration.
- Particularly effective for expansive clays and soft ground conditions.
- Electric currents can also facilitate the deep penetration of lime and chemical solutions, enabling treatment at greater depths.
- Suitable for small-scale and localized applications.

(2) Heat Treatment Method

- A technique that strengthens soil by applying heat to evaporate moisture and alter the mineral structure.
- Applicable to expansive soils, collapsible soils, and organic soils.
- High-temperature treatment modifies the soil structure to reduce expansiveness.
- Its use is limited due to significant energy demand.

CHAPTER 5. BASIC POLICY FOR INFRASTRUCTURE DEVELOPMENT PROJECTS RELATED TO PROBLEM SOILS

5.1 PROCEDURE FOR INFRASTRUCTURE DEVELOPMENT PROJECTS WITH PROBLEM SOIL RISKS

In promoting facility development projects in areas where problem soil risks are assumed, it is essential to properly assess the risks associated with problem soil. Accordingly, necessary measures should be taken to reduce the risks at various project stages, such as planning, design, construction and maintenance. Meanwhile, the accumulation of technical information and the track record of countermeasure works for problem soils is limited, and systematic and technical knowledge is not sufficient. Consequently, projects in areas where problem soils are distributed involve more uncertain risks compared to normal projects. Furthermore, the processes for collecting information on problem soils and analyzing and evaluating them are not established in standards and manuals and require specialized knowledge to carry them out.

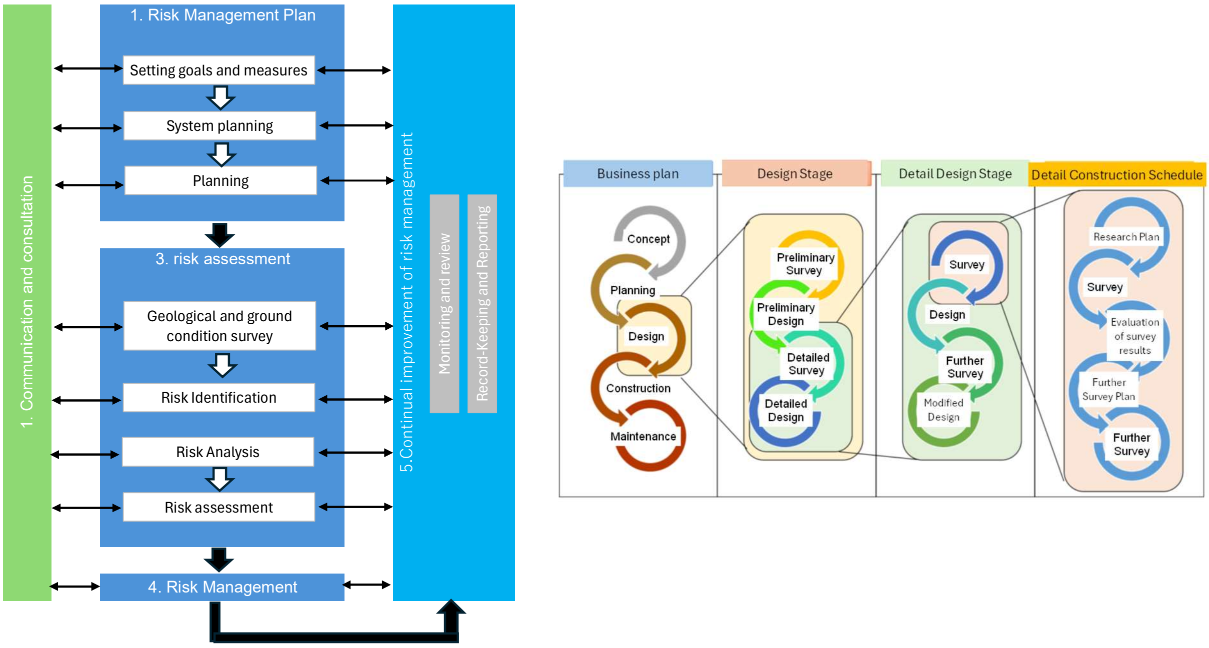
Therefore, when implementing a facility development project related to problem soils, it is important to take a risk management perspective, starting with the formulation of an appropriate project implementation flow and the establishment of a project implementation system. The system should include the assumption of risks and appropriate responses, the transfer of appropriate information on maintenance and management at the completion of the project, and the accumulation of information to reduce risks for future projects. The subsequent section describes the risk management aspects of the project.

This section delineates the essential concepts for undertaking facility development projects associated with problem soils.

5.1.1 Project implementation flow with problem soil risks

Generally, project implementation is carried based on waterfall methodology, following the sequence of conception, planning, design, construction and maintenance. In this regard, there is currently no standard protocol for addressing problem soils. Furthermore, depending on the extent of the problem, they may also impact the establishment of the project. Therefore, problem soil measures should not be carried out independently in a waterfall manner, but in an integrated manner, taking into account the feedback between the survey, planning and design, construction and maintenance of the infrastructure. This objective should be kept in mind at each stage of the survey, planning and design, construction and maintenance.

Based on the distribution situation of problem soils, the experience of operators in the target countries and examples of past ODA projects, risks are assumed at each stage of the project. These risks are based on the assumption that problem soils, if assumed, involve more uncertain risks compared to normal projects. It is important to proceed with the project while carrying out investigations and assessments , considering response measures, and monitoring those measures based on these assumptions. Given the risks assumed at the planning stage, it is necessary to consider and organize the roles and functions to be performed by each of the parties involved in the project (project proponent, financier, consultant, contractor, maintenance manager, etc.) and how they should work together. Information and awareness of risks must be constantly updated at each stage of the project. The Guidelines for Geological and Geotechnical Risk Management in Civil Engineering Projects (Technical Research Division, Minister's Secretariat, Ministry of Land, Infrastructure, Transport and Tourism/National Research Institute of Civil Engineering) can serve as a reference when undertaking a project. Figure 5.1.1 illustrates the risk management process and hierarchical structure outlined in these guidelines.



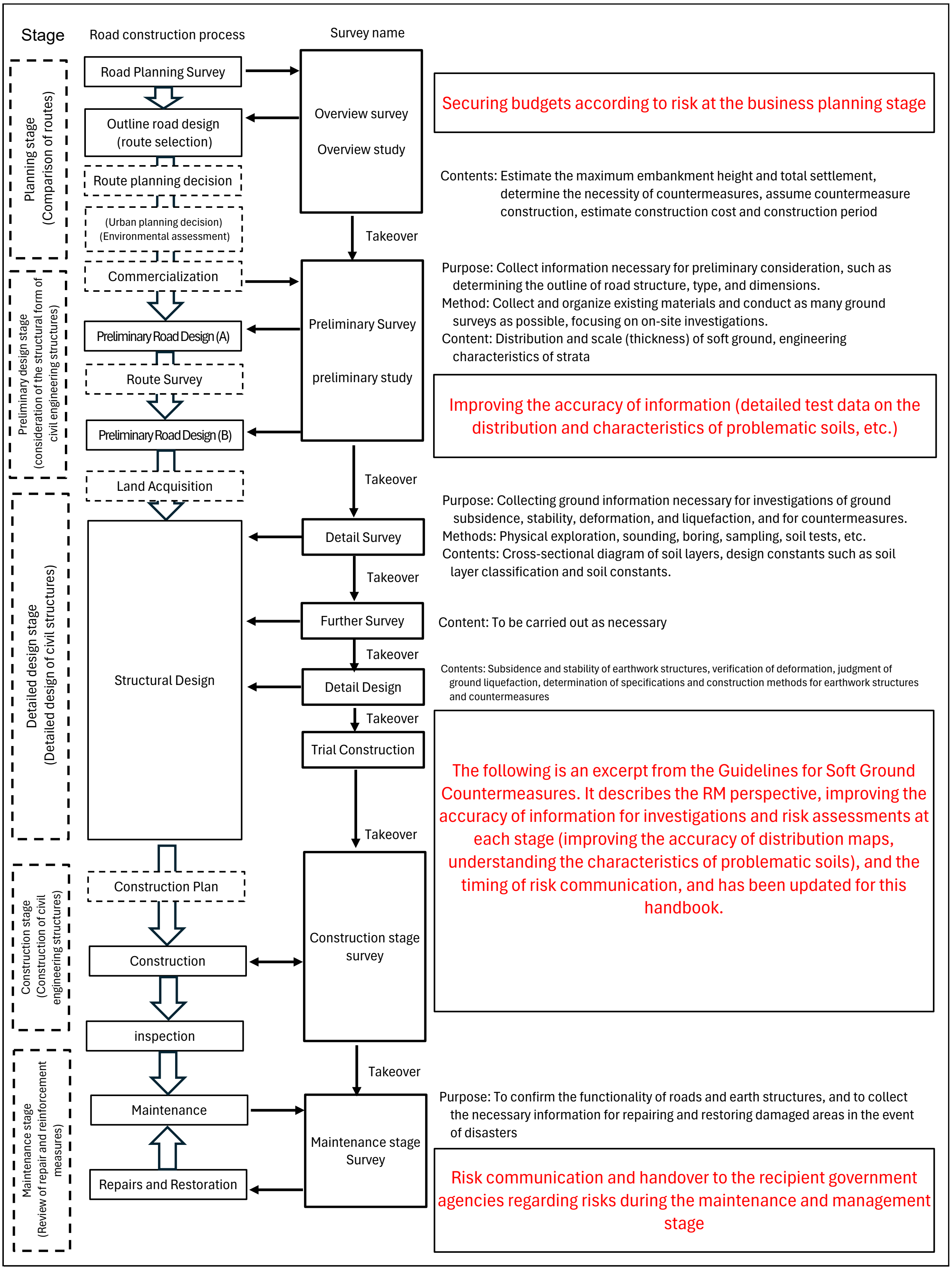
(a) Process of Geological and Geotechnical Risk Management (RM)

(b) Conceptual Hierarchical Structure of RM Process

Source: "Guidelines for Geological and Geotechnical Risk Management in Civil Engineering Projects" (March 2020, Ministry of Land, Infrastructure, Transport and Tourism / Public Works Research Institute)

Figure 5.1.1 Structure and Process of Risk Management

Based on these fundamental concepts, the flow of project implementation is shown in Figure 5.1.2, using road projects as an example.



Source: JICA Study Team

Figure 5.1.2 Project flow with possible risks related to problem soil (example of a road project)

5.1.2 Considerations for Establishing a System for Project Implementation Based on Problem Soil Risks

(1) System and organization for problem soil risk management

When implementing a project where risks associated with problem soils are anticipated, it is not necessary to establish a uniform system and organization. However, it is essential to implement the project using the most appropriate system that can be adopted at the time of project implementation, according to the objectives and characteristics of the project. When developing the system and organization, the project proponent should examine the division of roles among the parties involved and secure the necessary parties to ensure that the system is equipped with the capacity and functions to deal with the risks. This should take into account the characteristics of the geological and geotechnical risks associated with the problem soil in the project and the magnitude of the impact.

When implementing overseas projects, stakeholders belonging to government agencies of the financier and recipient countries, international cooperation agencies, construction consultants and contractors will normally fulfill their designated roles. When implementing projects where risks related to problem soils are anticipated, it is necessary to ensure the involvement of these specialized technical experts, as they are required to have specialist knowledge in the management of these risks. Specialist engineers to be assigned to each organization may include those with appropriate qualifications related to geology and geotechnics, etc., and experts in geological and geotechnical risks.

If the current structure and organization are expected to lack the necessary competence and knowledge, it may be necessary to consider supplementing the necessary competence and organization from within and outside the project. If the evaluation of geological and geotechnical risks associated with problem soils and the difficulty of dealing with them is high, it is advisable to consider adopting a committee format, etc., or holding meetings of interested parties, including research institutions. After determining the parties involved in these risk management activities, operators need to assign roles and functions and establish a system for their collaboration. The participating parties should confirm the roles and functions allocated to them and endeavor to ensure that their capabilities and functions are fully demonstrated.

(2) Review of the system and organization

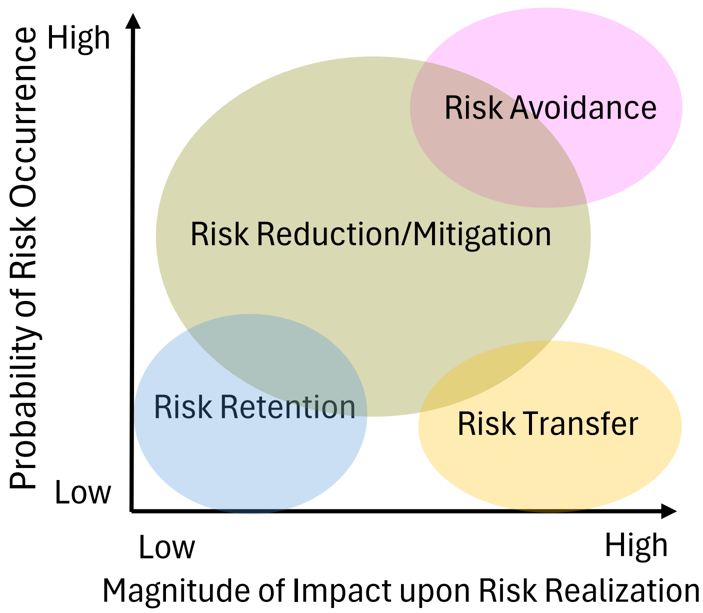
It is important that geological and geotechnical risk management is continuously promoted throughout the entire project, at each stage, and for each unit of work or construction. Additionally, it is necessary to consider reviewing the organization and structure in line with progress.

Even in the middle of the risk management process, it is important to regularly assess and enhance the functions and capabilities of the system and organization. This should be done promptly in the event of any concerns and in accordance with the project's progress. In such a review, it is important to monitor information on risks and the status of the system for dealing with them as the business progresses.

5.1.3 Risk response approach for problem soils

Given the highly uncertain nature of the ground in projects involving problem soils, there is an elevated risk of project costs increasing and extension of construction period compared to normal projects. Therefore, it is essential to consider risk responses based on the concepts of risk avoidance, risk mitigation (reduction), risk retention and risk transfer (see Figure 5.1.3).

For instance, at the time of road construction, the following risk responses can be considered: risk avoidance, where areas assumed that problem soils are distributed are avoided; risk reduction, where measures are planned and implemented based on the anticipated problem soils; risk retention, where there is no proactive approach to address problem soils and repairs are made on an ad hoc basis; and risk transfer, where insurance and other risk mitigation measures are employed to cover and repair risks as they emerge.



Source: JICA Study Team

Figure 5.1.3 Conceptual diagram of the response to the four risks

5.2 RISK COMMUNICATION BETWEEN STAKEHOLDERS

For risks identified at each stage, communication and discussion for the purpose of sharing information and awareness among the parties involved is essential them to ensure the timely execution of necessary actions by all relevant parties. This collaborative process is the cornerstone of effective risk management.

It is important that methods of communication regarding risks, monitoring methods and timing be defined at the planning stage. Furthermore, information and awareness regarding risks should be shared among the parties concerned on an ongoing basis. Following the completion of construction works, it is also imperative to appropriately transfer the status of studies, the status at the time of construction, risks assumed at the time of service, and countermeasures to be taken upon handover of the facility to the operator.

(1) It is essential that business stakeholders engage in continuous communication and consultation to ensure they maintain current awareness of risk and align their approach accordingly. Internal communication and consultation

It is necessary to have a function that facilitates the discussion of facility performance including soil structures that are integral to the design and structural works of projects and structures. This function should also encompass the dissemination of information regarding nature, risks, and uncertainties of problem soils estimated from geotechnical investigations and tests, etc., along with sharing awareness of potential risks posed by problem soil. The purpose of such a meeting is not only to share information, but also to prevent risks from being overlooked or misjudged, to clarify the extent to which risks can be addressed at a given point in time for the purpose of considering the optimal time to address risks, and to unify responses to risks in cases where multiple operations or construction projects converge. It is important to clarify the purpose of the project and adhere to that objective during execution.

(2) Communication and consultation with external parties

Communication and consultation should not only be conducted internally within the project, but also with external parties. The geological and geotechnical risks associated with problem soils are influenced by the external conditions of the project, such as the project's objectives, requirements and demands, as well as the environment.

(3) Consideration for risk visualization

The intricacies of risk factors and mechanisms, along with the uncertainties associated with problem soils, can be challenging to comprehend even for specialists involved in civil engineering projects. This complexity stems, in part, from ongoing establishment of technical and systematic knowledge, including investigation and testing methodologies, and countermeasure technologies, for each type of problem soil. Therefore, when communicating and discussing matters, it is desirable to ensure that the materials and explanations used are clear and easily comprehensible. This will enable all relevant parties to fully grasp the risks involved and share their respective perceptions.
When communicating and discussing civil engineering projects with external parties, it is important to remember that some individuals individualsmay not have a general understanding of such projects. To ensure clarity, it is advisable to avoid technical jargon and complex expressions when providing explanations.

(4) Communication and discussion on handover between project phases

The project is carried out through the following phases: conception, planning, design, construction, and maintenance. As the composition of the parties involved in the project changes at each phase, it is important to ensure the transfer of information between project phases. To ensure a seamless transfer of risks related to problem soils, it is important to prepare materials at each stage that summarize potential risks, uncertainties, and responses. These materials should be communicated and discussed to facilitate the adoption of appropriate responses (e.g., considerations during construction and maintenance) in subsequent stages.

5.3 SURVEY APPROACH FOR PROBLEM SOIL

In the risk management process for problem soils, investigations of geological and geotechnical conditions are conducted to identify uncertainties and to obtain data for risk identification, analysis, and evaluation. As testing and evaluation methods for each type of problem soil have not yet been established, it is necessary to collect information on the problem soil in advance and develop a survey plan. As the project progresses, it is also essential to enhance the precision of the information and risk assessment, and to initiate the investigation process. This will ensure that the appropriate risk responses can be implemented at each project stage.

(1) Investigation plan

The investigation plan is designed to identify, analyze, and evaluate uncertain risks associated with problem soils, and to plan investigation contents, items, and tests to obtain information on the distribution range, characteristics, and countermeasure construction of the target problem soil with the accuracy required for each project stage. Given the absence of well-established testing and evaluation methods for problem soils, and the potential inadequacy of survey items and tests based on the relevant standards, the involvement of geological and geotechnical engineers in the planning and execution of appropriate surveys is essential.

(2) Investigation flow

The procedure described below should be followed for geological and geotechnical investigations related to problem soils with uncertain risks.

Arrangement of information on geology, ground, and distribution pertaining to the problem soil by desk study and geological survey

Arrangement of uncertainties (geological and geotechnical uncertainties related to problem soils, design and construction uncertainties, etc.)

Estimated performance of the soil and structures such as embankment considering uncertainties (considering the range of possible uncertainties) and risk factors related to the problem soils

Identification of risks by comparing the estimated performance with the required performance of the soil and structures such as embankments related to the problem soil.

(3) Collection and utilization of information on surrounding projects, topography, geology/soil, weather, etc.

It is essential to collect and utilize as much information as possible from the public and government agencies in the counterpart country that is useful for risk management of problem soils. This could include detailed topographical maps, information on previous geological and geotechnical surveys, surveys and designs of projects conducted in the vicinity, construction records. Collecting this information will reduce uncertainty related to the prediction of and measures for the behavior of problem soils. Efforts are made to reduce uncertainties related to the prediction of the behavior of problem soils and the measures to be taken.

In the early stage of a project, it is important to assess topographical information, geology and soil characteristics, and weather conditions including rainfall, prior to conducting a field survey. If specific information pertaining to the behavior of problem soils and countermeasures is available for surrounding projects, it is possible to accurately identify the risks that may occur and the appropriate measures to be taken. However, if there is a possibility that problem soils may be distributed but the available information is limited, the project plan should take the risks into account.

(4) Geological and geotechnical investigation and testing

In geological and geotechnical investigations, as in ordinary investigations, topography, geology and other data collected in (3) are investigated. Then, boring, exploratory drilling, and in-situ sounding are conducted to understand and organize the detailed distribution of problem soils and strata containing risks, and to identify risk locations in the project. Laboratory tests (including tests required for each problem soil) will be conducted using samples collected from in-situ tests to understand the characteristics, physical property data and behavior of the problem soil. To ensure the integrity of the project, surveys should be conducted at each stage with the necessary precision to identify potential risks and formulate effective responses. As the project progresses, it is essential to enhance the accuracy of these surveys.

(5) Arrangement of risks related to problem soil

1) Uncertainty

Organize risks due to uncertainties. In general, risk factors include the following, so the necessary items should be organized.

- Natural factors (geology, soil, groundwater, etc.: predisposing factors)
  - ➢ Uncertainty in the properties and behavior of problem soils
  - ➢ Uncertainty in the characteristics and behavior of the problem soil
  - ➢ Uncertainty in the occurrence of geological and geotechnical hazards
  - ➢ Uncertainty of environmental impacts due to ground and groundwater
  - ➢ Uncertainty of the existence and behavior of groundwater, underground gas, etc.

- Human-caused factors (factors of the people involved and their responses: inducements)
  - ➢ Uncertainty in the design and construction of problem soils
  - ➢ Uncertainty in the management of facilities and foundations
  - ➢ Uncertainty in communication and response to geological and geotechnical information related to problem soils

Uncertainties in the characteristics and behavior of problem soils and in the design and construction for problem soils are not always clearly addressed in ordinary projects, and in many cases cannot be quantitatively demonstrated.

Uncertainties in the characteristics and behavior of problem soils and those in the design and construction for problem soils are not always clearly addressed in ordinary projects, and in many cases cannot be quantitatively demonstrated. However, since the arrangement of uncertainties is indispensable for estimating risks, efforts should be made to clearly indicate uncertain items and their degree, using empirical and qualitative methods as well. In particular, items for which the geological and geotechnical risks associated with problem soils are estimated to be significant should be examined by conducting additional investigations as necessary.

2) Organize geological and geotechnical requirements for problem soils

The geological and geotechnical performance requirements for problem soils are organized based on the design conditions of the facilities and structures. In general, the geotechnical and geotechnical performance requirements for civil engineering projects are as follows. More detailed requirements for each structure should be organized as necessary.

- Performance as supporting ground (including during construction)
    - Mechanical performance (strength, deformability, anisotropy, etc.)
    - Hydraulic performance (imperviousness, permeability, etc.)
    - Long-term stability (stability against settlement, liquefaction, weathering, erosion, etc.)
    - Performance of the project line and surrounding area (including during construction)
    - Slope stability (stability against landslide, collapse, etc.)
    - Environmental stability (safety of groundwater quality, etc.)

3) Estimated geological and geotechnical performance and identification of geological and geotechnical risks related to problem soils

Based on the results of geological and geotechnical investigations and tests, the estimated performance of the geology and soils with respect to the required performance items will be determined.

Based on the results of these investigations, geological and geotechnical risks are extracted. The following are examples of geological and geotechnical risk conditions.

- Items for which the estimated performance of the geology/soil may be less than the required performance of the geology/soil.
- Poor geological conditions or hazardous areas
- Uncertainty of geology/soil in significant construction.

For the extracted geological and geotechnical risks related to problem soils, the risk factors and characteristics should be summarized and organized Furthermore, consideration should be given to visualize the risks in a manner that is easy for relevant parties to understand, such as by clearly indicating the extent of the risks on plan and cross-sectional views. Examples of items to be organized for the extracted risks are shown below. It is desirable to organize these items to the extent possible. It is also desirable to organize the reasons, etc., for risks that were not identified as risks as a such of the review.

- Risk items
- Location and scope of risks
- Details of the risk (factors, predisposing factors and triggers, etc.)
- Magnitude of the consequence and its rationale (v) Likelihood and its rationale
- Likelihood of the consequences and the rationale for them

5.4 RECORDING, DOCUMENTATION AND REPORTING

In the risk management process related to problem soil, information obtained on risks related to problem soil and responses to those risks should be reported and shared among the relevant parties. Records should be prepared and the information handed over to the next stage.

In the risk management process related to problem soil, information obtained on risks related to problem soil and responses to those risks should be reported and shared among the parties concerned, records should be prepared, and the information should be handed over to the next stage.

(1) Reporting, Sharing, and Recording of Information

Information on geological and geotechnical risks related to problem soils should be reported and shared in communication and discussion forums. This allows project stakeholders, including the counterpart government and implementing agencies, to understand the risks at each stage of the project and take the necessary action. Examples of this type of information are shown below.

- Geological and geotechnical performance required for design and construction of projects and structures (performance requirements)
- Geological and geotechnical performance estimated by geological and geotechnical investigations and tests (estimated performance)
- Uncertainty of geology and groundwater and its effect on estimated performance
- Uncertainty of geological and groundwater conditions and their impact on estimated performance
- Geological and geotechnical risks (risk items, description, and results of risk analysis and assessment)
- Risk responses (proposed/selected risk responses and reasons)
- Residual risks

(2) Transfer of information

As the project proceeds to the next stage, the project proponent shall hand over the recorded information on geological and geotechnical risks associated with the problem soil and the status of the study up to that point to the relevant parties. TheseThe parties shall confirm the contents of the records, share information and awareness of challenges and examination methods through communication and consultation sessions. To ensure efficient use of this information throughout the project, itIt is recommended that information necessary for risk management be obtained and stored as electronic data during each process from survey and measurement to maintenance and management.

As described in the following chapters, risks related to problem soils may surface after construction of the facility is completed and it is put into service, or at an unexpected time. Information from the project implementation stage is useful for investigating the causes and considering appropriate countermeasures. Therefore, it is important to hand over data to the facility manager responsible for maintenance and management.

In particular, as described in the next chapter and beyond, risks related to problem soils may surface after construction of the facility is completed and the facility is put into service or at an unexpected time, and information at the project implementation stage is useful for investigating the causes and considering appropriate countermeasures, so it is also important to hand over data to the facility manager who is responsible for maintenance and management.

CHAPTER 6. ABOUT PROBLEM SOIL

6.1 DEFINITION OF PROBLEM SOIL

In this Handbook, the term “Problem Soil” refers to soils encountered in construction projects in developing countries that pose geotechnical challenges and are considered difficult to manage using the standard investigation, design, and construction practices commonly employed in Japan.

[Explanation]

The Geotechnical Society of Japan uses the terms “unusual soil” and “problem soil”, with the latter more closely aligned with the definition “soils that cannot be appropriately handled by conventional geotechnical engineering methods alone.” While “problematic soil” is frequently used in international literature to denote soils that cause engineering issues, this handbook adopts the term “problem soils” in accordance with the Japanese geotechnical context.

The term “problem soil” in Japan originated in the Temporary Measures Act for Special Land Area Disaster Prevention and Promotion (1952), which addressed soils highly susceptible to erosion, such as “Shirasu”, “Bora”, “Kora”, “Akahoya”, special volcanic ejecta and weathered Granite Soils.

However, many other types of problem soil exist globally. This handbook focuses on those with limited distribution in Japan and which are difficult to address using conventional Japanese practices.

In agricultural and soil science contexts, problem soils refer to soils unsuitable for cultivation. While differing from engineering-based classifications, systems such as Vertisols which include black cotton soils, a surface manifestation of expansive soils—can provide useful indicators for global distribution estimation.

Some locally specific soils are referred to as “local” or “regional” soils. These may have highly restricted distributions and may not be encountered in general construction or may be avoidable. Conversely, quick clay, prevalent in Northern Europe, is outside the scope of Japan’s ODA projects but is included here for reference.

Terminologically, both soil and soils are used in English, and domain-specific conventions vary:

- In geotechnical engineering and construction, terms such as problem soils, expansive soils, and dispersive soils are commonly used.
- In agriculture and soil science, expressions like saline soil or thermotropic soil are standard.

In literature, both expansive soils and expansive clays are used to describe swelling soils. Although expansive soils is a technically appropriate term, most such soils are clay-rich. Even certain rocks may disintegrate upon exposure (e.g., slaking), and as the weather and transition into soil, they exhibit problematic behavior similar to that of problem soils. Such materials are also treated as problem soils in this handbook.

6.1.1 Soil Formation Factors

> Soil formation is governed by six primary factors: parent material, topography, climate, biological activity, human activity, and time. These factors interact in complex ways to influence the development and characteristics of soil.

Vasily V. Dokuchaev, regarded as the father of soil science, first articulated that soil variation across regions is determined by climate, topography, and parent material. His theory was later refined by Hans Jenny, who formulated the relationship as:

Soil = f (climate, organisms, topography, parent material, time)

This conceptual model demonstrates that changes in any of these factors result in corresponding changes in soil properties.

For instance, weathering of bedrock—through thermal expansion/contraction or freeze-thaw cycles—produces regolith and finer mineral particles. These materials, under suitable climatic and topographic conditions, facilitate colonization by vegetation such as lichens and mosses.

As vegetation develops, organic matter accumulates through leaf litter and root decay, enriching the soil. Over time, this organic layer deepens, promoting further plant growth. Slope gradient, orientation, drainage conditions, and sediment inputs or losses all influence this development process.

Soil formation is thus a dynamic system reflecting the combined effects of natural and anthropogenic factors. Climate change can enhance or inhibit weathering and vegetation growth. Human activities—such as land clearing, drainage, fertilization, and deforestation—can also significantly alter soil processes and properties.

A summary of the principal soil-forming factors is provided in Table 6.1.1, categorized under five main headings: parent material, topography, climate, organisms, and time.

Table 6.1.1 Factors Influencing Soil Formation

Factor	Description
Parent Material	The type of parent material significantly influences soil formation. - Unconsolidated sediments transported by ice, water, wind, or gravity. - Weathered materials immediately overlying the consolidated hard bedrock. - Organic matter composed of decayed or partially decayed plant residues.
Topography	Topographic conditions influence soil formation by affecting regional climate, vegetation patterns, and water movement.
Climate	- Climatic Zone: Variations in temperature and moisture levels influence the weathering processes related to soil formation. - Temperature: The magnitude and fluctuation of temperatures impact soil formation processes. - Precipitation: The amount of precipitation affects the rate and type of soil-forming processes. - Soil Temperature: Influences the distribution of vegetation and biological activity within the soil. - Soil Moisture: Affects soil formation processes, as well as the use and management of soils.
Living Organisms	Plants and animals, ranging from microorganisms to humans, influence soil formation through biological processes.
Time	Physical, chemical, and biological processes acting over hundreds to thousands of years cumulatively impact soil formation.

Source: JICA Survey Team

6.2 SOIL FORMATION PROCESS

Soil formation is driven by biological, chemical, and physical processes. The principal mechanisms can be categorized into seven types: weathering; climate-related processes including humid conditions, humid tropical climates, arid tropical/subtropical climates, and cold climates; and deposition-related processes involving volcanic materials and water. Most soils are formed through a combination of these processes.

The characteristics of each soil type are determined by the pedogenic processes acting throughout its development. Biological, chemical, and physical mechanisms contribute to the addition, transformation, translocation, degradation, or removal of soil constituents. These processes cause soils to evolve over time in response to factors such as climatic variation and land use. Most soils form through multiple, distinct stages of development, reflecting the combined effects of these dynamic processes.

Table 6.2.1 summarizes the major soil formation processes, categorized into seven types:
weathering, moist conditions, humid tropical climate, arid tropical/subtropical climate, cold climate, volcanic materials, and water.

Table 6.2.1 Soil Formation Processes

Process	Description
Weathering	- Physical weathering: Soil formation through disintegration without altering the chemical composition. - Chemical weathering: Soil formation through progressive breakdown via chemical reactions.
Climate – Humid Conditions	- Leaching: Loss of minerals and organic solutes by percolating water. - Clay translocation: Movement or translocation of clay particles from one soil horizon to another. - Clay destruction: Destabilization of clay minerals and organic matter due to leaching of basic cations and accumulation of hydrogen ions, resulting in the collapse of clay structures.
Climate – Humid Tropical Conditions	- Highly weathered soils with iron accumulation: Formed under high soil temperatures and intense leaching, where all primary minerals dissolve, leaving iron and aluminum oxides, kaolinite clays, and coarse quartz grains. - Soils with characteristic nodular horizons: Soils derived from ferruginization processes, featuring shiny ped faces and polyhedral blocky structures rich in kaolinite and iron, typically red in color. - Soils with plinthic horizons: Formed by the segregation of iron under saturated conditions, leading to iron-rich, potentially hardening layers. - Soils with argillic horizons and low- or high-activity clays: Resulting from the vertical movement of clay, leading to horizons richer in clay content than the overlying layers.
Climate – Arid and Semi-Arid Tropical Conditions	- Soils with calcium carbonate accumulation: Formed by the downward movement and precipitation of $CaCO_3$, creating accumulation layers. - Soils with gypsum accumulation: Formed from parent materials containing gypsum, where evapotranspiration enriches the soil with gypsum. - Soils with silica accumulation: Formation of extremely hard layers rich in silica, characteristic of *Durisols* typically found in arid regions. - Soils with salt accumulation: Soils with salinity levels approximately 2,500 ppm.
Cold Climate	- Periglacial processes: Formation of patterned ground features such as frost heaving, soil mixing and sorting, cryoturbation, thermal cracking, surface crusting, ice lensing, and wedge ice accumulation due to freeze-thaw cycles.
Volcanic Materials	- Soils derived from volcanic ejecta: Formation of soils rich in volcanic glass from volcanic ash deposits.
Water-Formed Soils	- Hydromorphic soils: Soils such as groundwater gley soils, formed by prolonged saturation and reduction conditions due to water infiltration.

***Source**: JICA Survey Team*

6.3 CLASSIFICATION OF PROBLEM SOIL

Problem soils can be broadly classified into three categories based on their dominant characteristics: mechanical properties, chemical properties, and others.

- Mechanical Properties: expansive soils, dispersive soils, erodible soils, collapsible soils, crushable soils, soluble ground, soft ground
- Chemical Properties: saline/sodic soils, (acid) sulfate/sulfide soils, carbonate soils, acid soils
- Others: laterite, loess, volcanic ash soils, coral soils and coral aggregates, mica-rich sands, glacial deposits (till), weathered rock/soft rock, arid soils

[Explanation]

A wide range of soils exhibit problematic behaviors in geotechnical engineering. Such problem soils are characterized by excessive volume change, low shear strength, or susceptibility to erosion, all of which adversely affect the performance of structures and urban infrastructure. For example, expansive soils alone are estimated to cause annual economic losses of approximately €400 million in Europe and $15 billion in the United States—exceeding the combined damages from earthquakes, floods, hurricanes, and tornadoes.

As discussed in Chapter 1, soils develop through complex interactions of formation factors and processes. Thus, even visually similar soils may display significantly different engineering properties. In particular, problem soils often fall outside the bounds of conventional geotechnical classifications and theoretical frameworks, creating challenges in their identification, evaluation, and management.

To address these challenges effectively, the following steps are essential:

- Identification through geological, geomorphological, and pedological understanding
- Classification and assessment using correlations, laboratory testing, and in-situ investigation
- Evaluation through empirical, analytical, or numerical modeling
- Implementation of appropriate countermeasures via targeted engineering solutions

Problem soils may appear "abnormal" because their behavior deviates from classical soil mechanics theory. However, with proper investigation—through laboratory and field testing, as well as pilot construction—their characteristics can be reasonably understood and managed using suitable technologies.

Currently, no universally accepted classification system for problem soils exists in geotechnical engineering. A simple method for estimating global soil distribution involves climate-based classification—tropical, arid, temperate, continental, and polar/alpine zones—where different climatic conditions govern distinct soil formation processes. However, from an engineering perspective, classification by mechanical behavior (e.g., swelling, dispersibility, collapsibility) is often more practical, as it directly correlates with field performance. At the same time, chemical properties acquired during soil formation—such as salinity or acidity—can lead to additional engineering issues, including corrosion and deterioration of structures.

Certain soils cannot be neatly categorized by mechanical or chemical criteria alone. For instance:

- Laterite, common in tropical and subtropical regions, is not classified under standard systems.
- Volcanic ash soils vary widely—from cohesive loams to fragile materials like Shirasu.
- Pumice soils exhibit crushability.
- Mica-rich sands show unique behavior due to the platy shape of mica particles.
- In Indonesia, clay shale rapidly slakes upon exposure, transforming into soft, expansive clay.
- In Africa, schist, phyllite, and shale are known to weather and generate problem soils.
- Region-specific soils such as Sabkha and Marsh soils are also included in the broader classification.

Table 6.3.1 presents a classification of problem soils, grouped into three categories: mechanical properties, chemical properties, and others.

Table 6.3.1 Classification of Problematic Soils (Part 1: Soils by Mechanical Properties)

Category	Soil Type	Characteristics	Main Regions	Engineering Problems	Related Terms
Physical Properties	Expansive / Swelling Soil(Clay)	Clayey soils that exhibit significant expansion and shrinkage due to changes in moisture content. Rich in expansive clay minerals such as montmorillonite.	Arid and semi-arid regions with distinct dry and wet seasons.	Deformation associated with ground heave/settlement, structural cracking and subsidence, landslides/slope deformation, earth pressure generation due to swelling.	Black Cotton Soil, Bentonite, Smectite / Montmorillonite, Vertisols
	Dispersive Clay/Soil	Soils whose clay particles readily separate and disperse upon contact with water, leading to collapse. Predominantly composed of sodium-rich (Na^+) clays.	Arid and semi-arid regions.	Piping, cavity formation/sinkholes, slope erosion/collapse.	Eluviation of fines (silt/clay), Solonetz
	Collapsible Soil/Ground (Compressible Soil)	Soils that are stable when dry but collapse rapidly upon wetting.	Semi-arid to arid regions.	Wetting-induced subsidence (ground /foundation /embankment), slope failures.	Volcanic ash, Loess, Sabkha, Tropical soils, Quick Clay, Mudstone, Sandy soils
	Crushable Soil (Highly Compressible Soil)	Soils that are dense when dry but easily fracture or crush under external loads.	Volcanic regions, dry regions with abundant aeolian deposits.	Embankment /foundation settlement, inadequate ground/pile bearing capacity.	Loess, Volcanic ash, Sabkha, Tropical soils, Collapsible clay, Pumice, Particle crushing
	Erosive Soil (Fragile Soil)	Soils whose surface layers are eroded by wind or water, leading to loss of fertility.	Sloped terrains, arid regions, and high rainfall areas.	Landslides, slope erosion/gully erosion, riverbank erosion.	Loess, Saline soils, Sheet erosion, Aeolian erosion
	Soluble Ground	Ground containing easily water-soluble minerals (primarily limestone, dolomite, gypsum, rock salt), prone to void and sinkhole formation due to groundwater flow.	Regions rich in limestone, gypsum, or rock salt.	Subsidence, cavity formation, heterogeneous bearing capacity.	Limestone, Chalk, Gypsum, Rock Salt, Karst Topography, Sinkhole, Cave
	Soft Ground	Ground with low strength, high compressibility, and low bearing	Alluvial plains, deltas, wetlands,	Consolidation settlement, slope stability issues, inadequate bearing	Holocene deposits, Peat, Marine clay, Liquefaction

Category	Soil Type	Characteristics	Main Regions	Engineering Problems	Related Terms
		capacity, prone to settlement and deformation.	reclaimed lands, peatlands.	capacity. Special problematic soils include liquefiable loose sands, peats, and marine clays.	
Chemical Properties	Saline Soils	Soils with excessive salt accumulation at the surface or within the soil profile.	Arid and semi-arid regions; poorly drained lowlands.	Foundation and pavement cracking /settlement due to swelling; steel corrosion /degradation from salt attack; concrete neutralization /alkali-silica reaction; reduction of permeability. Dispersive issues arise in sodic soils.	Solonchak, Solonetz, Sabkha, Salina, Playa, Surface crusting
	Sodic Soils	Alkaline soils with excessive sodium (Na^+) accumulation, resulting in soil structure collapse and decreased permeability.	Arid and semi-arid regions, poorly drained irrigated areas.		
	Sulfate Soils	Soils rich in sulfate ions (SO_4^{2-}), typically containing gypsum ($CaSO_4$) or sodium sulfate (Na_2SO_4). High Na^+ content can lead to transition into sodic soils.	Saline-affected regions in arid and semi-arid zones, coastal wetlands.	Concrete/aggregate deterioration due to sulfate attack; swelling due to gypsum dissolution during wet periods and recrystallization during drying; void formation; ground subsidence; low bearing capacity; corrosion of metals and pipelines.	Gypsum ($CaSO_4 \cdot 2H_2O$), Sulfates, Sulfides, Reduced Pyrite (FeS_2), Calcium sulfate
	Sulfide Soils	Soils with sulfur-bearing organic matter (e.g., pyrite FeS_2) accumulated under reducing conditions; upon oxidation, they transform into strongly acidic soils (pH ~4), termed Acid Sulfate Soils.	Coastal wetlands, reclaimed lands, peatlands, estuarine areas.	Acidification-induced corrosion of concrete and reinforcing steel; soft ground conditions; low bearing capacity.	
	Carbonate Soils	Soils rich in carbonates (CO_3^{2-}), primarily formed through limestone weathering or salt accumulation. Contain calcium carbonate, magnesium carbonate (dolomite), or sodium carbonate.	Arid/semi-arid zones, karst regions, volcanic ash regions, marine regions (coral reefs).	Ground subsidence due to voids; differential settlement of roads, railways, and foundations; degradation of concrete/metal structures; corrosion of steel by salt attack; reduction of bearing capacity.	Limestone soils, Alkaline soils, Calcareous soils, Chalky soils, Marl, Shell/coral-bearing sands

Category	Soil Type	Characteristics	Main Regions	Engineering Problems	Related Terms
	Calcareous Soils	Alkaline soils containing abundant calcium carbonate ($CaCO_3$). Considered a subset of carbonate soils.		Coral-containing sands show behavior similar to crushable soils, requiring special consideration for pile design.	
Others	Laterite	Highly weathered soils rich in iron and aluminum oxides, tending to harden upon drying. Acidic in nature.	Humid tropical and subtropical regions.	Extremely hard when dry but softens and becomes unstable during wet conditions; hardened surfaces may overlay weak subsurface layers, leading to differential settlements. Rapid degradation of road pavements during rainy seasons when used as paving material.	Hardens upon drying; utilized as road construction material or for brick-making.
	Volcanic Ash Soils	Soils formed by the weathering of volcanic ejecta such as ash, scoria, and pumice; lightweight and highly porous.	Regions along mountainous belts.	Similar problems to soft ground conditions; crushable behavior due to high pumice content; slope instability.	Loam, Shirasu, Ashy soils, Low friction angle soils, Pumice, Scoria
	Sand Rich in Mica	Sandy deposits containing abundant mica minerals (muscovite, biotite, phlogopite) formed by weathering and erosion.	Regions with rich mica deposits or granitic terrains and river systems.	High compressibility, low shear strength, insufficient pile bearing capacity.	
	Glacial Sediment	Deposits transported and laid down by glacial activity; characterized by a heterogeneous mixture of grain sizes, affecting ground stability and drainage behavior. Composed of sand, gravel, silt, and clay.	High-latitude regions of the Northern Hemisphere and mountainous areas.	Structural heterogeneity, sudden strength loss (Quick clay phenomenon), freeze-thaw related issues.	Quick clay/sand, Till, Moraine, Angular particles, Outwash plains, Eskers, Drumlins
	Weathered Rock/Soft Rock	Weathered rock refers to rock that has undergone physical and chemical	Weathered rocks occur in hot and humid tropical to	Slaking into soft clay soils leading to slope failures and landslides; swelling behavior. When used	Clay shale, Claystone, Schist, Phyllite, Shale, Water-induced

Category	Soil Type	Characteristics	Main Regions	Engineering Problems	Related Terms
		degradation, reducing its strength and deformability. Soft rock inherently possesses low hardness regardless of rock type, allowing easy excavation.	temperate regions with old geological formations. Soft rocks are typical of sedimentary rocks (e.g., shale, mudstone, tuff) and easily weathered igneous rocks (e.g., andesite, tuff).	as embankment material, particle crushing under load causes settlement (crushable behavior), or water infiltration causes slaking-induced collapse (collapsible behavior).	settlement

***Source**: JICA Survey Team*

6.4 Problem Soil Distribution Area

> The distribution of problem soils has been compiled to the extent possible by major regions and countries.

[Explanation]

6.4.1 Distribution of Problem Soils

As fundamental reference information, the distribution areas of problem soils by major region—as well as the types of problem soils identified in each region and country—have been compiled to the extent possible in the appendix of this final research report. This information is intended to serve as a basic resource during the planning stages of international projects, including the formulation of investigation and research programs.

6.4.2 Creation of Problem Soil Distribution Map

> Based on the literature data collected and compiled in this research project, an original estimated distribution map of problem soils has been developed. The map focuses on problem soils commonly encountered worldwide, including expansive soils, dispersive soils, collapsible soils (loess), and laterite.

[Explanation]

6.4.2.1 Overview

This handbook presents a problem soil distribution map for globally widespread problem soils, specifically swelling soils, dispersive soils, and laterite. The maps were developed using QGIS, a free and open-source GIS platform, to ensure accessibility and usability by a wide range of users.

The base data was derived from the Harmonized World Soil Database Version 2.0 (HWSD), which provides global soil coverage. This was supplemented and refined with regional distribution data obtained through literature reviews and expert interviews.

In addition to the problem soil distribution map, a country-specific risk map was created to offer a preliminary understanding of problem soils and their associated risks in developing countries. Although factors such as population density and infrastructure importance would ideally be included to enhance the precision of risk assessment, the current map is intended for early-stage project planning and provides only a broad indication of potential risks.

It is acknowledged that even for the same soil classification, risk levels may vary significantly depending on geographic context and distribution patterns. Therefore, there is a future need to develop more refined, high-resolution risk maps that support detailed evaluations at the national level, extending beyond preliminary assessments.

Table 6.4.1 Overview of Problem Soil Distribution Map Creation

Item	Contents
Purpose	To support understanding and risk awareness regarding problem soils when undertaking business activities in developing countries
Target Problem Soils	The following problem soils were covered due to their common global occurrence: ・Swelling soils ・Dispersive soils ・Collapsible soils (loess) ・Laterite For other soils, available literature-based distribution information is provided where applicable.
Maps Provided	・Estimated Problem Soil Distribution Map (JICA original) ・Risk Map
Software Used	・QGIS (free and open-source GIS software)
Creation Overview	・The base data source is the Harmonized World Soil Database Ver. 2.0 (HWSD), which provides global soil coverage. ・Additional refinements were made using regional data obtained from literature and interviews. The resulting data were reorganized and compiled into the distribution map. ・Based on the reorganized data, a risk map was developed to visualize the relative risk levels by country. Risk levels were classified based on the proportion of land area covered by problem soils: - High Risk: >30% - Medium Risk: 10–30% - Low Risk: <10%
Important Notes	The risk map reflects only the areal extent of problem soil distribution per country and does not incorporate other risk factors such as population density or infrastructure importance. It is therefore intended as a preliminary warning tool for early-stage planning in developing countries.

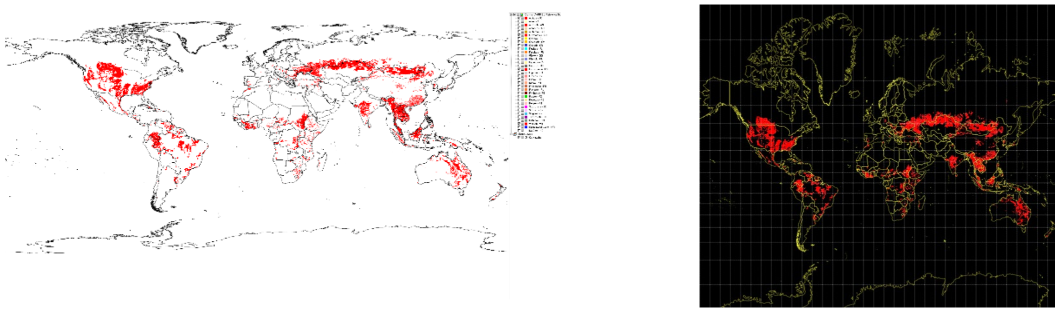
Source: JICA Study Team

6.4.2.2 Procedure for Creating an Estimated Problem Soil Distribution Map

This section outlines the procedure used to generate the estimated problem soil distribution map presented in this handbook.

(1) Creation of the Base Map

The global distribution maps for each type of problem soil, as provided in the appendix of this final report, were obtained from the Harmonized World Soil Database (HWSD) Ver. 2.0. These maps were imported into QGIS as raster data and used as the base layer for subsequent analysis.



(a) (b)

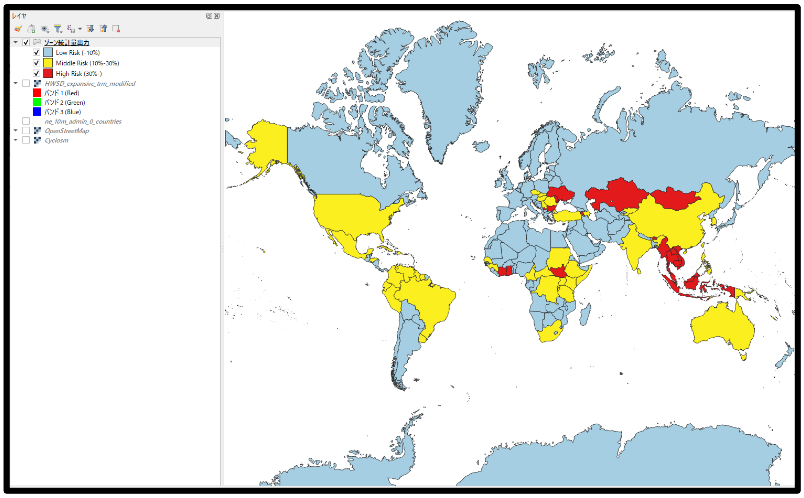
Source : HWSD Ver 2.0 , JICA Study Team

Figure 6.4.1 (a) Distribution map of HWSD and (b) base map on QGIS

(2) Creation of the Expected Distribution Map

Raster analysis was performed using QGIS to calculate the average raster value within the vector zones defined by national borders. These values were used to estimate the distribution ratio of problem soil relative to national land area, and countries were classified into three risk categories:

- High Risk: >30% coverage
- Medium Risk: 10–30% coverage
- Low Risk: <10% coverage

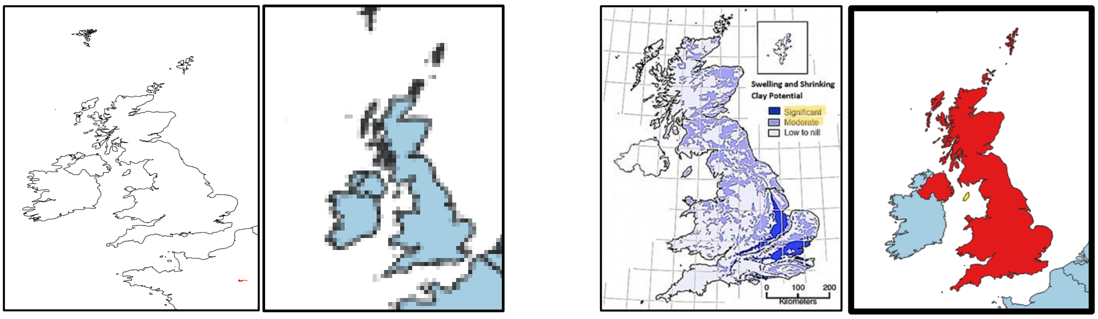


Source: JICA Study Team

Figure 6.4.2 Example of a predicted distribution map on QGIS

(3) Integration of Distribution Data from Existing Literature

Problem soil distribution data compiled from existing literature, as shown in the appendix of this report, were also imported into QGIS and subjected to raster analysis following the same method described above. The resulting statistical data were then incorporated into the estimated distribution map. The updated version is presented in Chapter 4: Responses at the Planning and Survey Stage of this handbook.



(a) HWSD base map and projected distribution map

(b) Previous literature data and updated estimated distribution map

Source: Enhancing the Engineering Properties of Subgrade Materials Using Processed Waste: A Review, Samuel Y. Amakye, Samuel J. Abbey, Colin A. Booth, Abdul-Majeed Mahamadu (2021)

Figure 6.4.3 Example of updating the assumed distribution map on QGIS

6.5 USE OF SOIL TAXONOMY

The Harmonized World Soil Database Version 2.0 (HWSD), a global soil classification database, provides soil distribution maps that show similarities with the global distribution patterns of problem soils such as expansive soils. Accordingly, it was utilized as a fundamental data source in the development of the problem soil distribution map presented in this handbook.

[Explanation]

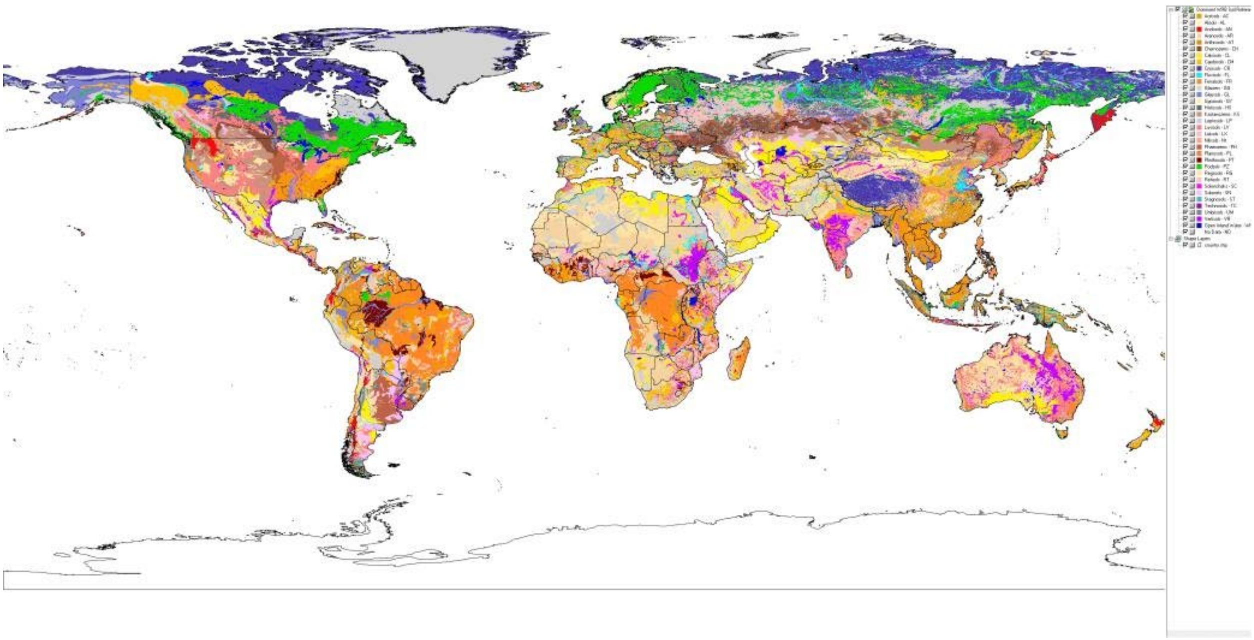
Although considerable research has been conducted on global soil classification maps, there is no established global distribution map specifically for problem soils. In the field of soil taxonomy, the two principal global classification systems are the World Reference Base for Soil Resources (WRB), 4th Edition (2022), and the USDA Soil Taxonomy, 13th Edition (2022). While WRB provides an internationally harmonized framework for soil classification, the USDA system was originally developed for agricultural applications in the United States.

The Harmonized World Soil Database Version 2.0 (HWSD v2.0), developed by FAO and IIASA, is a comprehensive global soil database that offers detailed information on morphological, chemical, and physical properties of soils at a spatial resolution of 1 km. It has become a valuable tool for research in areas such as agriculture, food security, and climate change impact assessment. The Windows-compatible platform facilitates global visualization of soil classifications and allows zooming in for detailed country-level information.

By leveraging HWSD data, it is possible to estimate the likelihood of the presence of problem soils in each country. For example, Vertisols are the representative soil group for swelling soils, while Chernozems, Acrisols, Luvisols, and Phaeozems may also exhibit expansive behavior.

When comparing the global distribution map of swelling soils and the HWSD-based estimation map of potentially expansive soils, a clear similarity in their spatial patterns can be observed. The appendix of this final report provides a summary of potential problem soils inferred from HWSD soil classifications. However, it should be noted that these are only estimations, as limited literature exists directly linking specific soil taxonomic groups to engineering problem soils.

Accordingly, this handbook uses the HWSD as the primary reference for constructing the problem soil distribution maps.



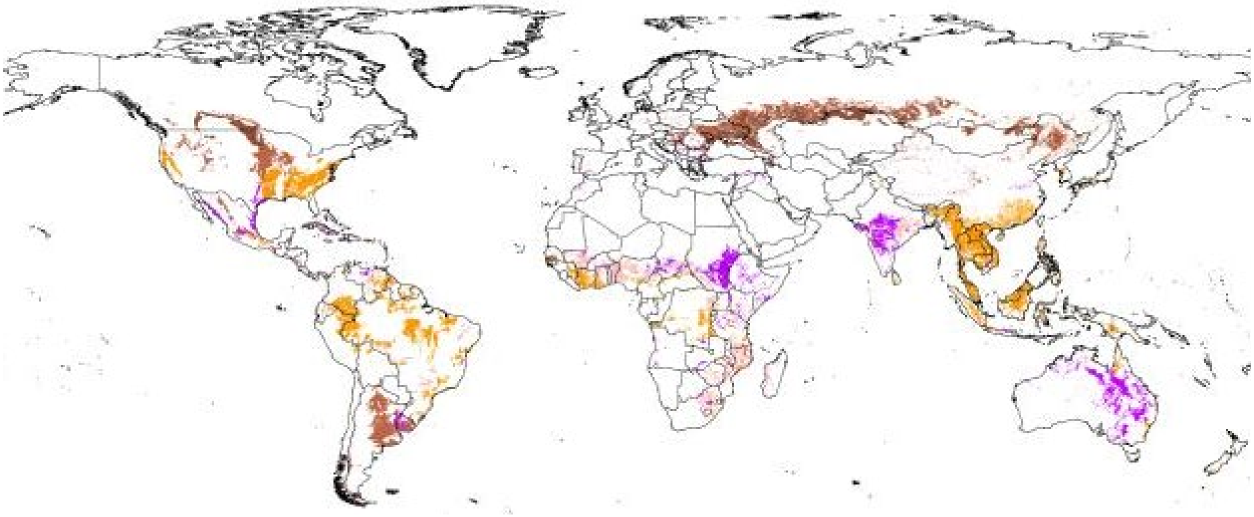
Source: https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v20/en/

Figure 6.5.1 Example of the worldwide display of the Harmonized World Soil Database v2.0

Figure 1 – Global distribution of shrink–swell soil where major construction costs occur (by region)

Sources: Swelling and shrinking soils, Jones, Lee; Banks, Vanessa; Jefferson, Ian. 2020

Figure 6.5.2 Global distribution of swelling soils



Source: JICA Study Team

Figure 6.5.3 Potential soil distribution map of swelling soils using HWSD
(Vertisols , Chernozems, Acrisols , Luvisols , Phaeozems)

6.6 ENGINEERING PROBLEMS OF PROBLEM SOILS

With the growth of infrastructure in developing countries, encounters with problem soils during construction projects are expected to increase, and the need for appropriate countermeasure technologies is becoming ever more critical.

To address the challenges posed by problem soils, the following three aspects are essential:

1. Understanding the geological and geomorphological context related to problem soils
2. Establishing methods for evaluating and identifying the behavior of problem soils
3. Developing effective countermeasures and design methodologies

The geotechnical issues associated with problem soils vary depending on the soil characteristics, climatic conditions, and type of structure involved. Therefore, even when new mitigation technologies are developed, unforeseen problems may still arise under different conditions.

[Explanation]

Problem soils often necessitate modifications to conventional geotechnical engineering practices. A review of the literature indicates that many of these issues remain unresolved, and various types of problem soils continue to pose engineering challenges globally.

As infrastructure development expands—particularly in countries receiving ODA assistance—the number of construction projects encountering problem soils is expected to increase. Consequently, the frequency and severity of geotechnical problems associated with such soils will also rise. In parallel, growing emphasis on carbon reduction and climate resilience, aligned with international sustainability targets, as well as the intensification of extreme weather events, will further highlight the need for effective technologies to address problem soils.

Problem soils persistently cause significant engineering difficulties worldwide. To address these challenges, the following key aspects must be considered for each type of problem soil:

- Understanding the geological and geomorphological context of the soil
- Identifying the soil and establishing methods to evaluate and characterize its behavior
- Developing effective countermeasures and appropriate design approaches

Engineering problems associated with problem soils differ depending on the soil properties, climatic conditions, and the type of structure involved. The application of new construction technologies may introduce previously unencountered issues, and it is highly likely that unknown or poorly understood phenomena remain.

CHAPTER 7. CONCLUSION

This handbook has been compiled by summarizing the current knowledge and information based on the items collected and investigated in the research project 'Basic Study on Reinforcement Measures for Local Natural Geomaterials and Problematic Soil Measures Encountered in Construction Works in Developing Countries'. The standards, scientific papers and books collected have varying shades of detail for each problem soil. While expansive soils are relatively well documented, information on the properties, behavior, investigation methods and countermeasures for other problem soils is limited.

Issues related to problem soils have occurred in various projects in many countries around the world, and cases have been identified in which expansive soil, dispersive soil, collapsible soil, laterite and other types of problem soils have caused extensive damage to large areas or structures. Problem soils vary widely from region to region and have highly variable characteristics, and are an area where systematic investigation and research are insufficient. Countermeasures have not yet been established, and there have been many cases where risk avoidance is insufficient within the existing framework of soil engineering. Therefore, depending on the scale and content of the distribution of problem soils encountered or likely to be encountered, it is necessary to proceed with the project in a comprehensive and efficient manner. This requires taking into account feedback on road planning and design, including modifications to route and structure location, as well as structural changes, both large and small.

Although the technologies in Japan do not necessarily target problem soils distributed throughout the world, Japan has various excellent geotechnical technologies, such as treatment of soft soil which is often a problem in construction projects, stabilizing soil materials using cement materials and treating slopes. Regarding these technologies, various countries have high expectations for support projects, as shown in Table 7.1.1, to solve problems related to ground, including problem soils.

Table 1.1.1 Support projects related to special soils and ground expected in Japan

Category		Support Projects Expected from Japan
Technology transfer	Soft soil treatment	➢ Projects to promote Japanese ground improvement technologies (e.g. shallow, medium and deep soil improvement)
	Slope protection, treatment	➢ Projects for the dissemination of slope surface treatment technology (revegetation and structural works)
	Landslide prevention measures	➢ Projects to disseminate slope failure prevention technologies and landslide monitoring technologies
Technical assistance	Technical support	➢ Technical assistance for the development of manuals, standards and guidelines ➢ Technical assistance on strengthening the geotechnical information database ➢ Technical assistance on ground exploration and ground analysis, etc.
	Human resources training	➢ Technical support for engineer education programmes, laboratory soil testing, etc.
Financial assistance	Procurement of equipment, products	➢ Support for the development of an environment in which various material tests can be carried out
Joint research	SATREPS	➢ Joint research on concepts and design methods for investigation and countermeasure works for special soils

Source: JICA Study Team

Japanese technologies have the potential to be a powerful solution to the problems due to problem soils. Development studies aim to adapt these technologies to the local geotechnical conditions and soil materials. Examples include technology that improves the properties of expansive soils using relatively inexpensive chemical additives, mixing equipment that improves laterite to a stable quality, and filter materials that prevent erosion and surface collapse of slopes at relatively low cost.

It is important that research and studies on problem soils, including these technologies, are carried out to accumulate knowledge that will contribute to the implementation of safe, high-quality infrastructure construction projects. In addition, overseas development of Japanese technology for global contribution is highly desirable.

Finally, it is considered very effective for the future to accumulate a database of a series of information on cases encountered in projects, including the details of problem soils, measures taken and their effects, and feedback on the planning and design of infrastructure construction projects. It is anticipated that this handbook will serve as an inaugural step in this development process.

APPENDIX

APPENDIX A. METHOD OF IDENTIFYING EXPANSIVE SOIL BASED ON SOIL PROPERTIES

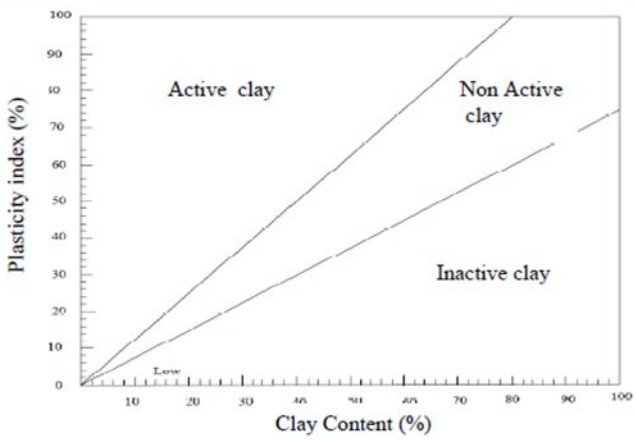


Figure (2.4): Soil classification chart (Skempton, 1953).

Source: Swelling Performance of some Expansive Soil Treatment Techniques, Mohamed Youssef Abd El-Latif(2008)

Figure A.1 Identification based on clay content and plasticity index (Skempton, 1953)

Table A.1 Identification based on shrinkage limit and linear shrinkage (Altmeyer, 1955)

Swelling Potential	Expected Swell	Shrinkage Limit (%)	Linear Shrinkage (%)
Non-critical	<0.5	>12	<5
Marginal	0.5~1.5	10~12	5~8
Critical	>1.5	<10	>8

Source: Swelling Performance of some Expansive Soil Treatment Techniques, Mohamed Youssef Abd El-Latif(2008)

Table A.2 Identification based on shrinkage limit, plasticity index, and colloidal content (Holtz and Gibbs, 1956)

Degree of Expansion	Protential swell (Total volume %)	Soil Index Properties Data		
		Shrinkage Limit (%)	Plasticity Index	Colloidal Content (less than 0.001 mm)
Low	<10	>15	<18	<15
Medium	10~30	10~16	15~28	13~23
High	20~30	7~12	25~41	20~33
Very High	>30	<11	>35	>28

Vertical surcharge: 1.0 psi ≈ 6.89 kPa

Note: Revisions by JICA Study Team (marked in red)

Source : Swelling Performance of some Expansive Soil Treatment Techniques, Mohamed Youssef Abd El-Latif(2008)

Table A.3 Identification based on liquid limit and plasticity index (Williams, 1958).

Degree of Expansion	Liquid Limit (%)	Plasticity Index
Low	<50	<25
Medium	50~60	25~35
High	>60	>35

Source：Theoretical Approaches and Advanced Construction Technologies for Expansive Soil Treatment, Yang Guolin, Liu Yihu, and Huang Xiangjing (2008)

Table A.4 Identification based on shrinkage limit, plasticity index, and colloidal content (Holtz and Gibbs, 1959)

Degree of Expansion	Shrinkage Limit (%)	Plasticity Index	Colloidal Content (% less than 0.001 mm)
Low	>15	<18	<5
Medium	10~16	15~28	13~23
High	7~12	25~41	20~31
Very High	<11	>35	>28

Vertical surcharge: 1.0 psi ≈ 6.89 kPa

Note: Revisions by JICA Study Team (marked in red)

Source：Swelling Performance of some Expansive Soil Treatment Techniques, Mohamed Youssef Abd El-Latif(2008)

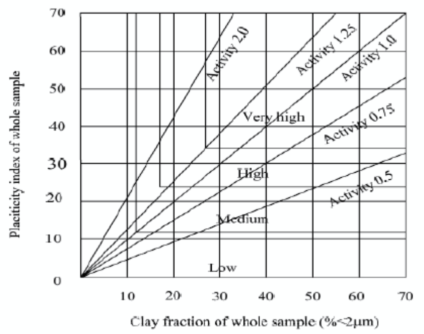


Figure (2.5): Swell potential as function of colloids content and Activity (Seed et al., 1960)

Source：Swelling Performance of some Expansive Soil Treatment Techniques, Mohamed Youssef Abd El-Latif(2008)

Figure A.2 Identification based on clay fraction content and plasticity index (Seed et al., 1960).

Table A.5 Identification based on swelling Potential and plasticity index (Seed et al., 1962).

Swelling Potential	Swelling Potential S	Plasticity Index (%)
Low	0~1.5	0~10
Medium	1.5~5	10~20
High	5~25	20~35

$$Swelling\ potential\ S = 1.10^{-5} {I_p}^{2.24}$$

Source：Swelling Performance of some Expansive Soil Treatment Techniques, Mohamed Youssef Abd El-Latif(2008)

Table A.6 Identification based on Swelling Potential and plasticity index (Holtz, Seed, and Woodward).

Swelling Potential	Holtz & Gibbs Swelling Ratio (%)	Seed et al. Swelling Ratio (%)	Colloidal Content (%)	Shrinkage Limit (%)	Free Swell Index (%)
Low	<10	0~1.5	<17	<15	<50
Medium	10~20	1.5~5	12~27	15~30	50~100
High	20~30	5~25	18~37	30~60	100~20
Very High	>30	>25	>27	>60	>200
Note	7kPa	7kPa	%-0.001mm	-	-

Source：Prediction of Swelling Behavior of Expansive Soils Using Modified Free Swell Index, Methylene Blue and Swell Oedometer Tests, Jaleh Forouzan, Amir(2016.02)

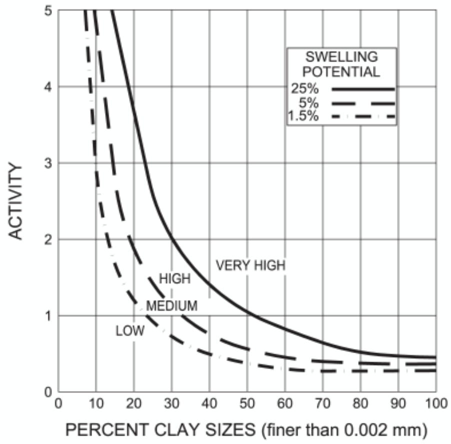


FIGURE 9.2. Swelling potential for compacted clays based on activity and percent clay (Seed, Woodward, and Lundgren 1962).

Source：Foundation Engineering for Expansive Soils, J. D. Nelson, K. C. (Geoff) Chao, D. D. Overton, E. J. Nelson, John Wiley & Sons(2015)

Figure A.3 Identification based on clay fraction content and activity (Seed et al., 1962).

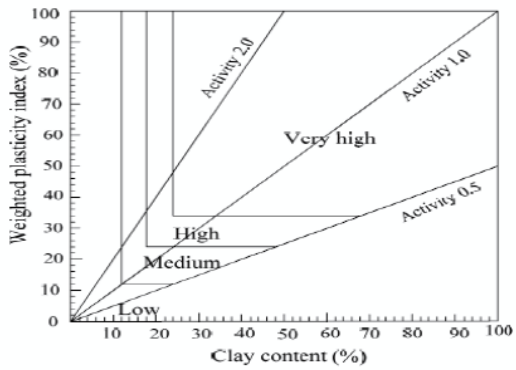


Figure (2.6b): Potential severity of volume change for clay soils (Van Der Merwe, 1964).

Source：Swelling Performance of some Expansive Soil Treatment Techniques, Mohamed Youssef Abd El-Latif(2008)

Figure A.4 Identification based on clay fraction content and plasticity index (Van der Merwe, 1964).

Table A.7 Identification based on shrinkage index (Ranganatham and Satyanarayana, 1965).

Swelling Potential	Shrinkage Index
Low	0~20
Medium	20~30
High	30~60
Very High	>60
Extreme High	>130

Source : Swelling Performance of some Expansive Soil Treatment Techniques, Mohamed Youssef Abd El-Latif(2008)

Table A.8 Identification based on expansion index (Uniform Building Code, 1968).

Swelling Potential	Expansion Index
Low	0~20
Medium	21~50
High	51~90
Very High	91~130
Extreme High	>130

$$Expansion\ IndexEI = 100 \times \Delta h \times F$$

Where: Δh = swell ratio (%), F = percentage passing the No. 4 sieve (4.75 mm)

Source : Swelling Performance of some Expansive Soil Treatment Techniques, Mohamed Youssef Abd El-Latif(2008)

Table A.9 Identification based on shrinkage index and plasticity index (Sowers and Sowers, 1970).

Degree of Expansion	Plasticity Index (%)	Shrinkage Limit (%)
Low	<15	>12
Medium	15~30	10~12
High	>30	<10

Source : Swelling Performance of some Expansive Soil Treatment Techniques, Mohamed Youssef Abd El-Latif(2008)

Table A.10 Identification based on shrinkage index and plasticity index (IS 1498, 1970).

Degree of Expansion	Liquid limit (%)	Plasticity Index (%)	Shrinkage Limit (%)	Free Swell Index (%)
Low	20~35	<12	<15	<50
Medium	35~50	12~23	12~30	50~100
High	50~70	23~32	30~60	100~200
Very High	70~90	>32	>60	>200

Source : Swelling Behaviour of Expansive Soil, Vikram Kumar, Dhirendra Kumar(2011)

Table A.11 Identification based on plasticity index (Peck, Hanson, and Thornburn, 1974).

Degree of Expansion	Plasticity Index(%)
Low	0~15
Medium	0~35
High	20~55
Very High	>35

Source : Peck, Hanson, and Thornburn 1974

Table A.12 Identification based on shrinkage index and liquid limit (Snethen et al., 1975).

Degree of Expansion	Plasticity Index, PI (%)	Raman(1967)	Ranganatham et al.(1965)	Ladd et al.(1961)
		Shrinkage Index (%)	Shrinkage Index (%)	Liquid limit (%)
Low	<12	<15	<20	20~35
Medium	12~23	15~30	20~30	55~50
High	23~32	30~60	20~30	50~70
Very High	>32	>60	>60	70~90
Extreme High	-	-	-	>90

Source : Swelling Performance of some Expansive Soil Treatment Techniques, Mohamed Youssef Abd El-Latif(2008)

Table A.13 Identification based on liquid limit (Chen, 1975).

Degree of Expansion	Chen	IS 1498
	Liquid limit (%)	Liquid limit (%)
Low	<30	20~35
Medium	30~40	35~50
High	40~60	50~70
Very High	>60	>70

Source : Prediction of Swelling Behavior of Expansive Soils Using Modified Free Swell Index, Methylene Blue and Swell Oedometer Tests, Jaleh Forouzan, Amir(2016.02)

Table A.14 Identification based on plasticity index (Chen, 1975).

Degree of Expansion	Holtz	Chen	IS 1498
	Plasticity Index (%)	Plasticity Index (%)	Plasticity Index (%)
Low	<20	0~15	<12
Medium	12~34	10~35	12~23
High	23~45	20~55	23~32
Very High	>32	>35	>35

Source : Prediction of Swelling Behavior of Expansive Soils Using Modified Free Swell Index, Methylene Blue and Swell Oedometer Tests, Jaleh Forouzan, Amir(2016.02)

Table A.15 Identification based on liquid limit, plasticity index, and suction (Modified from Snethen, Johnson and Patrick, 1977)

Degree of Expansion	Potential Swell (%)	Liquid limit (%)	Plasticity Index (%)	Suction	
				(pf)	(MPa)
Low	<0.5	<50	<25	<3.1	<1.3
Medium	0.5~1.5	50~60	25~35	3.1~3.6	1.3~4.0
High	>1.5	>60	>35	>3.6	>4.0

Source : Foundation Engineering for Expansive Soils, J. D. Nelson, K. C. (Geoff) Chao, D. D. Overton, E. J. Nelson, John Wiley & Sons(2015)

Table A.16 Identification based on liquid limit, plasticity index, and suction (Snethen et al., 1977).

Degree of Expansion	Potential Swell (%)	Liquid limit LL (%)	Plasticity Index Ip (%)	Suction	
				(ton/ft2)	(MPa)
Low	<0.5	<50	<25	<1.5	<0.16
Medium	0.5~1.5	50~60	25~35	1.5~4.0	0.16~0.43
High	>1.5	>60	>35	>4.0	>0.43

Source : AN EXPERIMENTAL STUDY ON THE TREATMENT OF EXPANSIVE SOILS BY GRANULAR MATERIALS, Hergul Timucin(2019)

Table A.17 Identification based on plasticity index (Snethen, 1980).

Degree of Expansion	Plasticity IndexPI(%)
Low	<18
Medium	22~32
High	22~48
Very High	>35

Source: Swelling Performance of some Expansive Soil Treatment Techniques, Mohamed Youssef Abd El-Latif(2008)

Table A.18 Identification based on plasticity index (Neil, 1980).

Degree of Expansion	Potential Swell (%)	Liquid limit (%)	Plasticity Index (%)
Low	<0.5	<50	<25
Medium	0.5~1.5	50~60	25~35
High	>1.5	>60	>35

Source : Prediction of Swelling Behavior of Expansive Soils Using Modified Free Swell Index, Methylene Blue and Swell Oedometer Tests, Jaleh Forouzan, Amir(2016.02)

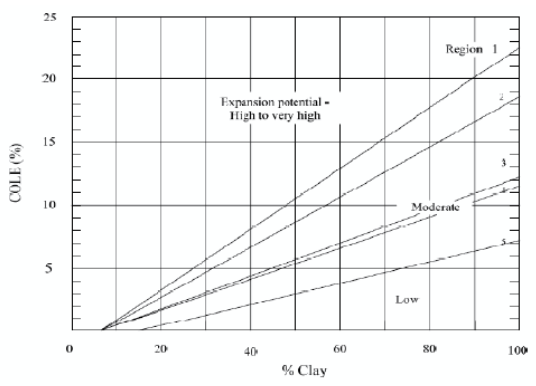


Figure (2.10): Swell potential as a function of colloids content and COLE (McKeen and Hamberg, 1981)

Source : Swelling Performance of some Expansive Soil Treatment Techniques, Mohamed Youssef Abd El-Latif(2008)

Figure A.5 Identification based on clay fraction content and COLE (McKeen and Hamberg, 1981)

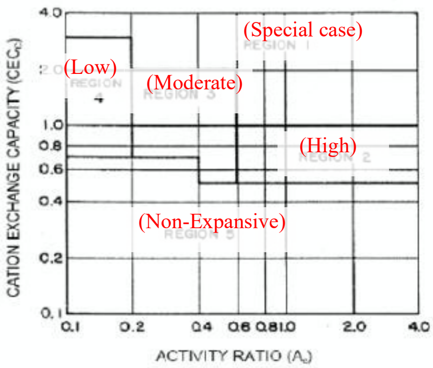


Figure (2.11): Soil expansiveness and COLE regions as a function of Activity and Cation Exchange Capacity (McKeen and Hamberg, 1981)

Source : Swelling Performance of some Expansive Soil Treatment Techniques, Mohamed Youssef Abd El-Latif(2008)

Red text: Added by JICA study team

Figure A.6 Identification based on activity and COLE (McKeen and Hamberg, 1981).

Table A.19 Identification based on field suction, plasticity index, and liquid limit (Snethen, 1984).

Degree of Expansion	Potential Swell (%)	Suction	Plasticity Index (%)	Liquid limit (%)
Low	<0.5	<1.5	<25	<30
Medium	0.5~1.5	1.5~4	25~35	30~60
High	>1.5	>4	>35	>60

Source : Swelling Performance of some Expansive Soil Treatment Techniques, Mohamed Youssef Abd El-Latif(2008)

Table A.20 Identification based on MFSI (Sridharan, 1986).

Degree of Expansion	MFSI (cm3/g)	Sedimentation volume in carbon tetrachloride (cm3/g)
Negligible	<1.5	1.10~3.00
Low	1.5~2.0	>1.1 and <MSFI
Medium	1.5~2.0	<1.1
High	2.0~4.0	<1.1
Very High	>4.0	<1.1

Source : Prediction of Swelling Behavior of Expansive Soils Using Modified Free Swell Index, *: Methylene Blue and Swell Oedometer Tests, Jaleh Forouzan, Amir(2016.02)*

Table A.21 Identification based on plasticity index, shrinkage limit, and liquid limit (Chen, 1987).

Degree of Expansion	Plasticity Index (%)	Shrinkage Limit (%)	Liquid limit (%)
Low	<18	>15	20~35
Medium	15~25	10~15	35~50
High	>35	7~12	50~70

Source : Swelling Performance of some Expansive Soil Treatment Techniques, Mohamed Youssef Abd El-Latif(2008)

Table A.22 Identification based on plasticity index, shrinkage limit, and liquid limit (Erol, 1987).

Degree of Expansion	Potential Swell (%)	Clay Fraction (%)	Plasticity Index (%)	Shrinkage Limit (%)
Low	<10	>15	<18	>15
Medium	10~20	13~23	15~25	10~16
High	20~30	20~31	25~41	7~12
Very High	>30	>28	>35	<11
Note	-	<2 μ m	-	-

Source : AN EXPERIMENTAL STUDY ON THE TREATMENT OF EXPANSIVE SOILS BY GRANULAR MATERIALS, H. Timucin(2019)

Table A.23 Identification based on swelling pressure, liquid limit, and fines content (Puvvadi, 1987).

Degree of Expansion	Liquid limit (Volume) (%)	Modified Free Swell Index
Low	<200	<2.5
Medium	200~400	2.5~10
High	400~550	10~20
Very High	>550	>20

$$Modified\ free\ swell\ index = \frac{V - V_s}{V_s}, LL_{volume} = \frac{LL_{mass}}{LL_{mass} + 100\rho_w/\rho_{dry}} \times 100$$

Where: V = volume after swelling, Vs = volume of soil solids=$W_s/(G_s\gamma_w)$

Source : Modified Free Swell Index for clays, Puvvadi V. Sivapullaiah Thallak G. Sitharal and Kanakapura S. Subba Rao(1987)

Table A.24 Identification based on swelling pressure, liquid limit, and fines content (Chen, 1988).

Degree of Expansion	Swelling Pressure (After 6 Years) (MPa)	Liquid limit (%)	Fine content %<74 μ m
Low	<0.05	<30	<30
Medium	0.15~0.25	30~40	30~60
High	0.25~1.0	40~60	60~95
Very High	>1.0	>60	>95

Note: Revisions by JICA Study Team (marked in red)

Source : Swelling Performance of some Expansive Soil Treatment Techniques, Mohamed Youssef Abd El-Latif(2008)

Table A.25 Identification based on Swelling Pressure, Liquid Limit, and Fines Content (Modified Chen, 1988)

Degree of Expansion	Fine content %<74 μ m	Liquid limit (%)	N value	Probable Potential Swell (Total volume) (%)	Swelling pressure (ksf), (kPa)
Low	<30	<30	<10	<1	1 (48)
Medium	30~60	30~40	10~20	1~5	3~5, (144~239)
High	60~95	40~60	20~30	3~10	5~20, (239~958)
Very High	>95	>60	>30	>10	>20, (>958)

Vertical Load σ_i'=1,000 psf (48kPa)

Source : Foundation Engineering for Expansive Soils, J. D. Nelson, K. C. (Geoff) Chao, D. D. Overton, E. J. Nelson, John Wiley & Sons(2015)

Table A.26 Identification based on Plasticity Index (Carter and Bentley, 1991)

Degree of Expansion	Potential Swell (%)	Plasticity Index (%)	Plasticity Index (%)
Low	0~1.5	0~15	0~15
Medium	1.5~5	10~30	15~24
High	5~25	20~55	25~46
Very High	>25	>40	>46

Source : Swelling Performance of some Expansive Soil Treatment Techniques, Mohamed Youssef Abd El-Latif(2008)

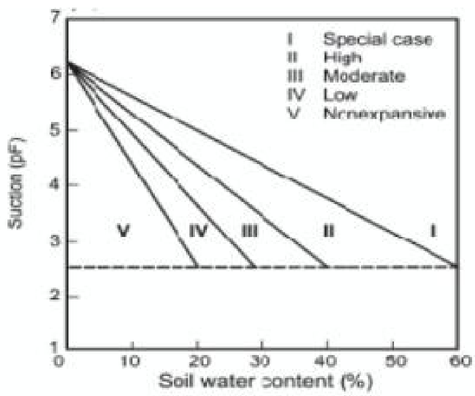


Figure (2.12): Example of the relationship between soil suction and water content (McKeen, 1992)

Source : Swelling Performance of some Expansive Soil Treatment Techniques, Mohamed Youssef Abd El-Latif(2008)

Figure A.7 Identification based on Water Content and Suction (McKeen, 1992)

Table A.27 Identification based on Plasticity Index (BRE, 1993)

Volume change potential	Plasticity IndexIp'(%)
Low	<20
Medium	20~40
High	40~60
Very High	>60

$$I_p' = I_p \times \frac{(\%425\mu m)}{100}\%$$

Source : Institution of Civil Engineers Manuals series CHAPTER C5 – EXPANSIVE SOILS Lee D Jones, British Geological Survey

Table A.28 Identification based on Expansion Index (ASTM D4829, 1995)

Degree of Expansion	EI (%)
Very Low	0~20
Low	21~50
Medium	51~90
High	90~130
Very High	>130

Source : Prediction of Swelling Behavior of Expansive Soils Using Modified Free Swell Index, : Methylene Blue and Swell Oedometer Tests, Jaleh Forouzan, Amir(2016.02)

Table A.29 Proposed Table-Based Classification of Swell Potential and Associated Slab Performance Risk (CAGE, 1996)

Slab Performance Risk	Typical Potential Swell (%)	
	σ v=500psf (29.9kPa)	σ v=1,000psf (47.9kPa)
Low	0~3	0~2
Medium	3~5	2~4
High	5~8	4~6
Very High	>8	>6

Source : Foundation Engineering for Expansive Soils, John D. Nelson, Kuo Chieh (Geoff) Chao, Daniel D. Overton, Erik J. Nelson (Wiley, 2015)

Table A.30 Identification based on Free Swell Index (IS 2720 Part 40, 1997)

Swell Shrink potential	Free Swell Index FSI
Low	<20
Medium	20~35
High	35~50
Very High	>50

$$COLE = {}^{\Delta L}/_{\Delta L_D} = \left({}^{\gamma_{dB}}/_{\gamma_{dM}}\right)^{0.35} - 1$$

Source : Foundation Engineering for Expansive Soils, John D. Nelson, Kuo Chieh (Geoff) Chao, Daniel D. Overton, Erik J. Nelson (Wiley, 2015)

Table A.31 Identification based on Colloid Content, Plasticity Index, and Shrinkage Limit (USBR, 1998)

Degree of Expansion	Potential Swell (%)	Clay Content (%)	Plasticity Index (%)	Shrinkage Limit (%)
Low	<10	<15	<18	>15
Medium	10~30	13~23	15~28	10~16
High	20~30	20~33	25~41	7~12
Very High	>30	>28	>35	<11
Note	-	<0.001mm	-	-

Source : Highway Engineering on Expansive Soils, Zheng Jianlong and Yang Heping (2009)

Table A.32 Identification based on Methylene Blue Value, Plasticity Index, and Shrinkage Limit (Claudial, 2000)

Swell/Shrink Potential	Methylene Blue Value VB (g/100gsoil)	Plasticity Index (%)	Swell Pressure SP'(kPa)
Low	<2.5	<12	0~100
Medium	2.5~4.5	12~35	100~300
High	4.5~9	35~45	300~500
Very High	>9	>45	>500

Source : Prediction of Swelling/Shrinkage Potential Using the Blue Methylene Method: some Examples in Italian Clayey Soils, M. Claudial(2000)

Table A.33 Identification based on COLE (Coefficient of Linear Extensibility) (Thomas et al., 2000)

Swell/Shrink Potential	Cole
Low	<0.03
Medium	0.03~0.06
High	0.06~0.09
Very High	>0.09

$$COLE = {}^{\Delta L}/_{\Delta L_D} = \left({}^{\gamma_{dB}}/_{\gamma_{dM}}\right)^{0.35} - 1$$

where, $\Delta L/\Delta Lp$ = linear strain relative to the dry dimension, γ_{dB} = dry density of the specimen after oven drying、 γ_{dM} = dry density of the specimen under suction of 5 psi (34 kPa).

Source : Swelling Performance of some Expansive Soil Treatment Techniques, Mohamed Youssef Abd El-Latif(2008)

Table A.34 Identification based on Liquid Limit (Sridharan, 2000)

Degree of Expansion	Chen	IS 1498
	Liquid limit (%)	Liquid limit (%)
Low	<30	20~35
Medium	30~40	35~50
High	40~60	50~70
Very High	>60	70~90

Source : Classification procedures for expansive soils, A. Sridharan and K. Prakash(2000.12)

Table A.35 Identification based on Plasticity Index (Sridharan, 2000)

Degree of Expansion	Holtz	Chen	IS 1498
	Plasticity Index (%)	Plasticity Index (%)	Plasticity Index (%)
Low	<20	0~15	<12
Medium	12~34	10~35	12~23
High	23~45	20~55	23~32
Very High	>32	>35	>32

Source : Classification procedures for expansive soils, A. Sridharan and K. Prakash(2000.12)

Table A.36 Identification based on Free Swell Index (Sridharan, 2000)

Degree of Expansion	Potential Swell(%)	Free Swell Index
Neglegible	<1	<1.0
Low	1~5	1.0~1.5
Medium	5~15	1.5~2
High	15~ 2 5	2~4
Very High	>25	4

Source : Prediction of Swelling Behavior of Expansive Soils Using Modified Free Swell Index, Methylene Blue and Swell Oedometer Tests, Jaleh Forouzan, Amir(2016.02)

Table A.37 Identification based on Colloidal content, Shrinkage Limit, Shrinkage Index, Free Degree of Expansion, and Potential Swell (Sridharan, 2000)

Degree of Expansion	Colloidal content (%)	Shrinkage Limit (%)	Shrinkage Index Is (%)	Free Swell Index (%)	Potential Swell (%)	Potential Swell (%)
Low	<17	>13	<15	<50	<10	0~1.5
Medium	12~27	8~18	15~30	50~100	10~20	1.5~5.0
High	18~37	6~12	30~60	100~200	20~30	5~25
Very High	>27	<10	>60	>200	>30	>25
Note	%-0.001mm	-	-	-	Holtz, 7kPa	Seed, 7kPa

Source：Classification procedures for expansive soils, A. Sridharan and K. Prakash(2000.12)

Table A.38 Identification based on MSFI (Sridharan, 2000)

Degree of Expansion	Potential Swell(%)	MSFI(cm3/g)	Free Swell Index
Neglegible	<1	<1.5	<1.0
Low	1~5	1.5~2.0	1.0~1.5
Medium	5~15	1.5~2.0	1.5~2.0
High	15~25	2.0~4.0	2.0~4.0
Very High	>25	>4.0	>4.0
Note	7kPa	-	-

$$MFSI = \frac{V_d}{10}\ ,\ Fee\ swell\ ratio = \frac{\text{蒸留水中の沈降体積}}{\text{四塩化炭素中の沈降体積}}$$

where, Vd = sediment volume in distilled water

Source：Classification procedures for expansive soils, A. Sridharan and K. Prakash(2000.12)

Table A.39 Identification based on Clay Fraction and Plasticity Index (Bekkouche et al., 2001)

Degree of Expansion	Clay Content <2 μ m (%)	Plasticity Index (%)
Low	<30	<18
Medium	30~60	18~22
High	60~95	22~35
Very High	>95	>35

Source：Swelling Performance of some Expansive Soil Treatment Techniques, Mohamed Youssef Abd El-Latif(2008)

Table A.40 Identification based on colloidal content、Plasticity Index、Shrinkage Limit (CMC., 2004)

Degree of Expansion	Potential Swell (%)	Colloidal Content (%) (-0.001mm)	Plasticity Index (%)	Shrinkage Limit (%)
Low	<10	<15	<18	>15
Medium	10~20	13~23	15~28	10~16
High	20~30	20~31	25~41	7~12
Very High	>30	>28	>35	<11

Source：Foundation Engineering for Expansive Soils, John D. Nelson, Kuo Chieh (Geoff) Chao, Daniel D. Overton, Erik J. Nelson (Wiley, 2015)

Table A.41 Identification based on Clay Fraction and Plasticity Index (CMC, 2004)

Degree of Expansion	Standard Absorbed Moisture Content (SAMC) (%)	Plasticity Index (%)	Free Expansion Index
Non-Expansive	< 2.5	< 15	< 40
Low	2.5~4.8	15~28	40~60
Medium	4.8~6.8	28~40	60~90
High	> 6.8	> 40	> 90

$$SAMC(\%) = \frac{W_c - W_s}{W_s}$$

Wc = bulk density measured at 77°F (25°C) and 60% relative humidity, Ws= oven-dry density of the specimen

Source : Foundation Engineering for Expansive Soils, John D. Nelson, Kuo Chieh (Geoff) Chao, Daniel D. Overton, Erik J. Nelson (Wiley, 2015)

Table A.42 Identification based on Swelling Pressure (Musso & Pejon, 2006)

Degree of Expansion	Swelling Pressure (kPa)
Low	<75
Medium	75~200
High	200~500
Very High	>500

Source : Expansive soils engineering geological mapping - applied method in clayey soils of Montevideo, Urguay, M. MUSSO & O. PEJON(2006)

Table A.43 Identification based on Colloidal content, Plasticity Index, and Shrinkage Limit (ACPA, 2008)

Degree of Expansion	Probable Potential Swell (%) (from dry to saturated condition)	Colloidal content (%) (-0.001mm)	Plasticity Index (%)	Shrinkage Limit (%)
Low	<10	< 15	< 8	>15
Medium	10~20	15~28	15~28	10~16
High	20~30	28~40	24~41	7~12
Very High	>30	> 40	>35	<11

Source : Expansive Soils TS204.2P, ACPA(2008)

Table A.44 Classification According to the Yang Shiji Standard (Yang Shiji Standard, 2008)

Degree of Expansion	Liquid limitLL(%)	Plasticity IndexIp(%)	Potential Swell(%)	Suction(kPa)	CBRSwell (%)
Low	40~50	18~25	0.7~2	100~160	1~2
Medium	50~60	25~35	2~4	160~440	2~3
High	>60	>35	>4	>440	>3

Source : Theoretical Approaches to Expansive Soil Treatment and New Engineering Construction Technologies, Yang Guolin, Liu Yihu, and Huang Xiangjing (2008)

Table A.45 Classification According to the Ministry of Construction Standard (GBJ 112–87, 2008 Edition)

Degree of Expansion	Free Swell Index (%)	Surface Deformation (mm)
Low	40~65	15~35
Medium	65~90	35~70
High	>90	>70

Source : Treatment Theories and New Construction Technologies for Expansive Soils, Yang Guolin, Liu Yihu, and Huang Xiangjing (2008)

Table A.46 Classification According to the Ministry of Transport Standard (JTG D30-2004, 2004)

Degree of Expansion	Free Swell Index (%)	Standard Hygroscopic Moisture Content (%)	Plasticity Index (%)
Non-Expansive	<40	<2.5	<15
Low	40~60	2.5~4.8	15~28
Medium	60~90	4.8~6.8	28~40
High	>90	>6.8	>40

Source : Theories of Expansive Soil Treatment and New Technologies for Engineering Construction, Yang Guolin, Liu Yihu, and Huang Xiangjing (2008)

Table A.47 Classification According to Li Shenglin (Li Shenglin, 2003)

Degree of Expansion	Liquid limit LL (%)	Potential Swell (%)	Plasticity Index Ip (%)	Natural Moisture Content (%)	Free Swell Index (%)	Climatic and Hydrogeological Conditions
Low	40~45	0.7~2	<18	>35	40~55	Better
Medium	45~50	2~4	18~25	25~35	55~70	Typical
High	50~55	4~6	25~35	15~25	70~85	Low
Very High	>55	>6	>35	<15	>85	Very Low

Source : Theoretical Approaches to Expansive Soil Treatment and New Technologies for Engineering Construction, Yang Guolin, Liu Yihu, and Huang Xiangjing (2008)

Table A.48 Classification According to Liu Tehong (Liu Tehong, 1997)

Degree of Expansion	Free Swell Index (%)	Potential Swell (%)	Swelling Pressure (kPa)	Liquid limit LL (%)	Plasticity Index Ip (%)	Internal Friction Angle ϕ (°)
Low	40~65	<2	<40	15~45	<18	>16
Medium	65~90	2~4	40~120	45~50	18~25	13~16
High	>90	>4	>120	>50	>25	<13

Source : Theoretical Approaches to Expansive Soil Treatment and Innovative Engineering Construction Technologies, Yang Guolin, Liu Yihu, and Huang Xiangjing (2008)

Table A.49 Classification According to Zheng Jiaxi (Zheng Jiaxi, 1999)

Degree of Expansion	CBR0.9 (%)	Potential Swell (%)	Liquid limit (%)	Plasticity Index (%)
Low	2~4	2~4	40~55	<20
Medium	1~2	4~5	55~65	20~26
High	<1	>6	>65	>26

Source : heoretical Approaches to Expansive Soil Treatment and New Engineering Construction Technologies, Yang Guolin, Liu Yihu, and Huang Xiangjing (2008)

Table A.50 Identification based on Free Swell Expansion (Highway Engineering on Expansive Soils, 2009)

Degree of Expansion	Free Swell Expansion (%)	Free Swell Expansion (%)
Low	40~65	30~50
Medium	65~90	50~80
High	>90	>80

Source : Highway Engineering on Expansive Soils, Zheng Jianlong and Yang Heping (2009)

Table A.51 Identification based on Shrinkage Ratio (Ke Zunjing, 1977)

Degree of Expansion	Linear Shrinkage (%)	Volumetric Shrinkage (%)	Potential Swell (%)
Low	2~5	8~16	2~4
Medium	5~8	16~23	4~7
High	8~11	23~30	7~10
Very High	>11	>30	>10

Source : Theoretical Approaches to Expansive Soil Treatment and New Technologies for Engineering Construction, Yang Guolin, Liu Yihu, and Huang Xiangjing (2008)

able A.52 Identification based on Free Swell Index and Shrinkage Ratio (Highway Engineering on Expansive Soils, 2009)

Degree of Expansion	Shrinkage Ratio (%)	Linear Shrinkage (%)	Linear Shrinkage (%)	Volumetric Shrinkage (%)	Free Swell Index(%)
Low	8~12	4~6	0.7~2	8~16	30~50
Medium	12~18	6~8	2~4	16~23	50~80
High	>18	>8	>4	>23	>80
	No surcharge	No surcharge		Shrinkage Limit	

Source : Highway Engineering on Expansive Soils, Zheng Jianlong and Yang Heping (2009)

Table A.53 Identification based on Multiple Indicators (Highway Engineering on Expansive Soils, 2009)

Degree of Expansion	Clay content (%)	Liquid limit (%)	Plasticity Index (%)	Specific Surface Area (m^2/g)	CEC (mol/kg)	Shring/Swell Potential (%)
Low	<35	<40	<18	<150	<300	4~6
Medium	35~50	40~48	18~25	150~300	300~400	6~8
High	>50	>48	>25	>300	>400	>8
Note	<0.002mm	-	-	-	-	No load

Source : Highway Engineering on Expansive Soils, Zheng Jianlong and Yang Heping (2009)

Table A.54 Identification based on Multiple Indicators (Highway Engineering on Expansive Soils, 2009)

Degree of Expansion	Free Swell Index (%)	Montmorillonite Content (%)	CEC (NH4+)
Low	40~60	7~17	170~260
Medium	60~90	17~27	260~360
High	>90	>27	>360

Source : Highway Engineering on Expansive Soils, Zheng Jianlong and Yang Heping (2009)

Table A.55 Identification based on Plasticity Index (NHBC, 2011)

Degree of Expansion	Plasticity Index Ip'(%)
Low	10~20
Medium	20~40
High	>40

Source : Institution of Civil Engineers Manuals series CHAPTER C5 – EXPANSIVE SOILS Lee D Jones, British Geological Survey

Table A.56 Identification based on Plasticity Index (Kumar et al., 2011)

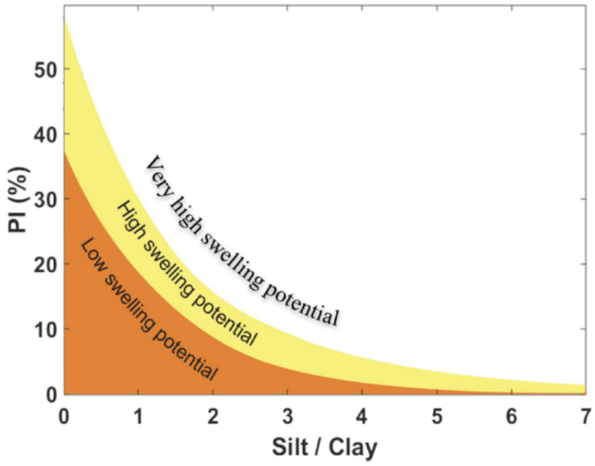
Degree of Expansion	Plasticity IndexIp'(%)
Low	0~15
Medium	15~35
High	35~55
Very High	>55

Source : I Swelling behaviour of expansive soil,Vikram Kumar, Dhirendra Kumar(2011)

Table A.57 Identification based on Shrinkage Limit and Linear Shrinkage (Kumar et al., 2011)

Degree of Expansion	Shrinkage Limit SL (%)	Linear Shrinkage (%)
Low	>12	0~5
Medium	10~12	5~8
High	<10	>8

Source : Swelling behaviour of expansive soil,Vikram Kumar, Dhirendra Kumar(2011)



Source : Predicting Soil Degree of Expansion Using Soil Classification Properties, Victor H. R. Barbosa, Maria E. S. Marques, Antônio C. R. Guimarães, 2023

Figure A8 Classification of Degree of Expansion Based on Silt/Clay Content and Plasticity Index (PI)

APPENDIX B. IDENTIFICATION OF EXPANSIVE SOIL AND DISPERSIVE SOIL BASED ON CHEMICAL INDICES

Table B.1 Identification of expansive soil and dispersive soil based on CEC

CEC (%)	Expansive Soil Identification	Dispersive Soil Identification
<10	Negligible	Negligible
10~30	Low	Low
30~50	Moderate	Moderate
50~80	High	High
>80	Very High	Very High

Source : JICA study team

Table B.2 Identification of expansive soil and dispersive soil based on ESP

ESP (%)	Expansive Soil Identification	Dispersive Soil Identification
<5	Negligible	Non-Dispersive
5~15	Low to Moderate	Partially Dispersive
15~25	High	Dispersive
25~40	Very High	Highly Dispersive
>40	Extremely High	Severely Dispersive

Source : JICA study team

Table B.3 Identification of expansive soil and dispersive soil based on SSA

SSA (m2/g)	Expansive Soil Identification	Dispersive Soil Identification	Major Clay Minerals
<10	Negligible	Negligible	Kaolinite
10~50	Low	Low	Illite
50~100	Moderate	Moderate	Illite + Montmorillonite
150~700	High	High	Montmorillonite
>700	Very High	Very High	Sodium Montmorillonite

Source : JICA study team

Table B.4 Behavior of expansive soil and dispersive soil based on alkalinity (pH)

pH	Soil Reaction	Expansive Soil	Dispersive Soil
<5	Acidic	Swelling potential decreases; clay particles tend to flocculate	Tends to resist dispersion
6～7	Slightly acidic to neutral	Swelling begins but not at maximum	Dispersion is somewhat suppressed
7～9	Neutral to slightly alkaline	Swelling potential reaches maximum	Tends to disperse more easily
9～10	Alkaline	Na^{+}-type montmorillonite continues to swell	Dispersion potential is at maximum
>10	Strongly alkaline	Ca^{2+}-type montmorillonite shows reduced swelling	Highly dispersive

Source：JICA study team

Table B.5 Identification of expansive soil and dispersive soil based on TP

TP (%)	Expansive Soil Identification	Dispersive Soil Identification
>1.5	Low	Low
0.5~1.5	Moderate	Moderate
<0.5	High	High

Source：JICA study team

APPENDIX C. TESTING STANDARDS IN JAPAN, THE UNITED STATES, AND THE UNITED KINGDOM

C1 LABORATORY SOIL TESTS

Table C.1 Standards for laboratory soil tests

Test name	Japan (JIS/JGS)	ASTM	BS/ISO	Others
Water Content Test	JIS A1203	ASTM D2216	BS 1377-2	
Density Test	JIS A1224	ASTM D2166	BS 1377-2	
Shrinkage Limit Test	JIS A1209	ASTM D4943	BS 1337-T-5	
Plasticity & Liquid Limit Test	JIS A1205	ASTM D4318	BS 1337-T2, T-4	
Particle Size Test	JIS A1204	ASTM D422	BS 1377-2	
Double Hydrometer Test	-	ASTM D4221	ISO 10930	
Free Swell Index Test	-	-	-	IS: 2720 (Part40)
Consolidation Test	-	ASTM D2435	ISO 17892	
Swelling/Collapse Test	-	ASTM D4546	ISO20315	
Rock Water Absorption Swell Test	JGS 2121	ASTM D5313	-	--
Test for the Coefficient of Linear Extensibility (COLE)	-	-	-	US DA, Natural Resources Conservation Service. National Soil Survey handbook (2024)
Expansion Index (EI)	-	ASTM D4829	-	
Pin Hole Test	-	ASTM D4647	-	
Crumb Test	-	ASTM D6572	-	
Single Particle Crushing Test	-	-	-	
Slaking Test	JIGS 2124, 2125	ASTM D4644	-	
Slake Durability Test	-	ASTM D464	BS EN ISO 14689?	

Source : JICA study team

C2 FIELD TESTS

Table C.2 Standards for field tests

Test name	Japan (JIS/JGS)	ASTM	BS/ISO	Others
Plate Load Test (Bearing Capacity)	JIS A 1215 JGS 1521	ASTM D1194 (Ground) ASTM D1195 (Road Base Course) ASTM D1195 (Pavement Base)	SO 22476-13	
Electric Cone Penetration Test (CPT)	JGS 1431	ASTM D5578	ISO 22476-1	
Borehole Horizontal Load Test	JIS A 1228:	ASTM D4719	ISO 22476-4	
Flat Dilatometer Test (DMT)	-	ASTM D6635	ISO 22476-5	

Source : JICA study team

C3 CHEMICAL ANALYSIS TESTS

Table C.3 Standards for chemical analysis tests

Test name	Japan (JIS/JGS)	ASTM	BS/ISO	Others
Cation Exchange Capacity (CEC)	JGS 0261 (Na+, K+, Mg2+, Ca2+)	ASTM D7503 (Na+, K+, Mg2+, Ca2+ et al.)	ISO 11260 (Na+, K+, Mg2+, Ca2+, Al3+, H+)	USDA Soil Survey Laboratory Methods Manual
Soluble Component Content Test	JGS 0241	ASTM D3987 (Waste)	(ISO 18772)	
Specific Surface Area (SSA)	JIS A 1475	STM D3663	ISO 9277	
Total Phosphorus (TP)	JIS K 0102	ASTM D4972	ISO 11263	USDA NRCS Soil Survey Laboratory Methods Manua
Electrical Conductivity of Saturation Extract (ECe)	JGS 0212 (JIS K 0123)	ASTM D1125	ISO 11265	USDA Handbook 60 FAO Irrigation and Drainage Paper 29
pH Test	JGS 0211	ASTM D4972	BS 1377-T-11 ISO 10390	
Water-Soluble Sulfate (WS)/Acid-Soluble Sulfate (AS)	JIS K 0102 JIS A 1226:	ASTM C1580 ASTM D4327 ASTM D516	BS 1377-3 ISO 9280 ISO 10304-1	
Total Sulfur (TS)	JIS K 0066 IS K 0102	ASTM D4239 ASTM D2492	ISO 15713 ISO 15178	
Total Recoverable Sulfate (TRS)	JIS K 0102: JIS A 1226	ASTM C114 ASTM D4327 ASTM D516	ISO 11048 ISO 10304 BS 1377-3	
Monosulfide Sulfur (MS)	JIS M 8814 JIS K 0102	ASTM D2492	ISO 11048 ISO 15713 ISO 4689-3	
Acid Drop Test	JIS A 1229	ASTM D5744 ASTM D8045	ISO 10693 ISO 15175 BS 1377-3:	
Calcimeter Method	JIS A 1225	ASTM D4373	ISO 10693 ISO 15178 BS 1377-3	
Lime Requirement Test	JIS A 1229	ASTM D3155	ISO 14254 BS 1377-3:	

Source : JICA study team

C4 SPECIALIZED TESTS

Table C.4 Standards for specialized tests

Test name	Japan (JIS/JGS)	ASTM	BS/ISO	Others
X-ray Diffraction (XRD)	JIS Z8828	ASTM D934	ISO 18309	
X-ray Fluorescence (XRF)	JIS Z 8825	ASTM E1621	ISO 13196	
X-ray Absorption Spectroscopy (XAS)	JIS K 0136	ASTM E572	ISO 20807	
Differential Thermal Analysis (DTA)	JIS K 7121	ASTM E793	ISO 11357-8 ISO 7111	
Differential Scanning Calorimetry (DSC)	JIS K 7121	ASTM D3418	ISO 11357-1	
Thermogravimetric Analysis (TG)	(JIS K 7120)		ISO 11358-3	
Energy Dispersive X-ray Spectroscopy (EDS/EDX)	JIS H7806	ASTM E1508	ISO 22309	
Scanning Electron Microscopy (SEM)	JIS Z2614	ASTM E766 ASTM E1588 ASTM E1588	ISO 16700 ISO 25498	IEC 62523

Source : JICA study team

APPENDIX D. PROBLEM SOIL Q&A

D1 GENERAL INFORMATION OF PROBLEM SOIL

No.	Question	Answer
1	What is "problem soil"?	In this handbook, "problem soil" refer primarily to soils encountered in construction projects in developing countries that present difficulties in survey, design, and construction. These soils are considered challenging to handle using methods commonly employed in Japan.
2	What types of problem soils exist?	Problem soils can be categorized into three main types based on their characteristics: "mechanical properties," "chemical properties," and "others." There are many different types, as outlined below: - Mechanical Properties: Expansive soils, dispersive soils, erosive soils, collapsible soils, shattering soils, soluble soils, soft soils - Chemical Properties: Saline/soda soils, (acidic) sulfate/sulfur soils, carbonate soils, acidic soils - Others: Laterite, loess, volcanic ash soils, coral soils and coral aggregates, sand with a high mica content, glacial deposits (icebound soils), weathered rock/soft rock, arid soils
3	How is problem soil identified?	Identification of problem soils is mainly carried out based on testing standards such as ASTM and methods proposed by researchers. For more details, please refer to the handbook. For some problem soils, such as dispersive soils, there are simple field methods available for identification.
4	Are there guidelines or standards for problem soils?	Some countries have developed guidelines and standards, but there are more countries without them. Even when guidelines and standards are available, they may not be sufficiently detailed due to the lack of established design and construction methods.

D2 EXPANSIVE SOIL

No.	Question	Answer
1	What are expansive soils?	Expansive soils are characterized by their capacity to swell when they absorb water during the rainy season and shrink when they lose moisture in dry conditions. These volume changes can cause significant cracking and structural distress to infrastructure and are a serious geotechnical concern worldwide.
2	In which regions are expansive soils distributed?	Expansive soils are widely found in: the United States (Texas, California), Asia (Thailand, Cambodia, Indonesia), India (Deccan Plateau, Black Cotton Soils), Australia, Africa (central and northern Nigeria, Nile basin in Sudan), South America (e.g., Orinoco basin in Venezuela), China (Sichuan Basin, parts of the Loess Plateau), and parts of Europe (e.g., France).
3	How are expansive soils identified?	Identification methods include: Physical properties: Liquid Limit, Plasticity Index, Free Swell Index Clay mineralogy: X-ray Diffraction (XRD), Differential Thermal Analysis (DTA), Scanning Electron Microscopy (SEM) Chemical analysis: Cation Exchange Capacity (CEC), Specific Surface Area (SSA), Total Potassium (TP) Mechanical testing: Consolidation test to determine Degree of Expansion (e.g., ASTM D4546). While consolidation tests are the most reliable, combining physical, mineralogical, and chemical approaches enhances the accuracy of evaluation.
4	How do expansive soils affect construction projects?	Effects include: structural cracks in buildings, pavement heaving and cracking, embankment deformation and slope failure, surficial slope

No.	Question	Answer
		collapses in cuttings, damage to canal banks and revetments, deformation or failure of retaining walls and buried structures, and uplift or failure of tunnel linings and base slabs.
5	What are the mitigation measures against expansive soils?	Effective measures include surcharge loading, soil replacement, chemical or thermal stabilization, and control of moisture and compaction. The selection of countermeasures must consider national standards, published guidelines, and local case studies to ensure suitability for site conditions.
6	What precautions should be taken in site investigations involving expansive soils?	Site-specific investigations are essential. Using regional soil data may overlook expansive behavior, potentially resulting in unconservative assessments. Detailed geotechnical investigations should be conducted at the actual location of the proposed structure.
7	White streaks observed in the clay—are they bentonite?	No. These white streaks are likely calcium precipitates, not bentonite. While they may indicate potential settlement due to high calcium content, they are not associated with swelling behavior.
8	If a structure heaves due to expansive soils, will the uplift stabilize after a few years?	No. Without a viable method to remove soil moisture from beneath the foundation, movement is likely to persist over time, although the magnitude may vary.
9	Is it true that expansive soils beneath foundations will settle if water sources are removed or prolonged drying occurs?	Not exactly. Moisture content beneath structures remains relatively stable, except directly below heat ducts or furnaces. When saturated, soils swell; once maximum expansion is reached, moisture may migrate to drier soil zones, causing continued heave.
10	Can chemical stabilization fully eliminate expansive soil problems?	No. Chemical stabilization technologies are still under development, and extensive research is needed—particularly for field applications—to achieve widespread and effective implementation.
11	Will expansive soil problems be avoided if the structure is built on elevated terrain?	Not necessarily. Even on elevated ground, high water tables can still trigger expansion, meaning issues may still occur.
12	Can pre-wetting the site before construction eliminate swelling problems?	No. Ponding water affects only shallow soil layers. Once the structure is built, swelling in deeper expansive soil layers can still occur, potentially causing damage.
13	Can proper surface drainage reduce the risk of foundation movement?	Yes, but drainage alone is insufficient to prevent heave or cracking. Appropriate structural design and construction practices are equally critical.
14	Can full pavement around the structure mitigate expansive soil issues?	Yes. Widespread pavement effectively prevents surface water infiltration into the foundation soils. This is one reason why gasoline stations in expansive soil regions report few instances of ground-related cracking.
15	Is it true that placing a sand/gravel layer beneath floor slabs reduces uplift pressure from expansive clay?	No. Expansive clays can exert uplift pressure against interlocked gravel particles, potentially causing slab heave.
17	Is it true that buried utilities should be avoided in expansive soil areas?	Yes. Expansive soils may shear water and sewer lines, leading to leaks. Initial minor leaks can induce further swelling, resulting in progressive damage and potentially severe structural issues.

D3 DISPERSIVE SOIL

No.	Question	Answer
1	What are dispersive soils?	Dispersive soils are clayey soils whose particles deflocculate and disperse into suspension upon contact with water. They are highly susceptible to internal erosion, often leading to structural failure through progressive piping or surface erosion initiated by minor disturbances.
2	In which regions are dispersive soils found?	Dispersive soils are reported in a wide range of regions, including: Cambodia (Mekong and Tonle Sap floodplains), Australia (Tasmania), Thailand (northeastern region), South Africa (Senekal

No.	Question	Answer
		Dam), the United States (Great Lakes and prairie regions), Greece, India (humid and riverine areas), Latin America, Indonesia (Java, Sumatra), Zimbabwe, China (Yangtze and Yellow River basins), Bangladesh (Ganges–Brahmaputra Delta), Nigeria (Niger and Benue River basins), Israel (Mediterranean coast, Jordan Valley), Iran, Spain, Ukraine (Black Sea to Chernobyl region), Brazil, New Zealand, Mexico, and Vietnam.
3	How are dispersive soils identified?	Four primary laboratory tests are commonly used for identification, though none are independently definitive; a combination is recommended for reliable evaluation. At a minimum, the Double Hydrometer Test and Crumb Test should be conducted. Typically, the Crumb Test is used for preliminary screening, followed by the Double Hydrometer Test for confirmatory assessment. The tests include: Crumb Test Double Hydrometer Test Pinhole Test Chemical Analysis
4	How do dispersive soils affect construction?	Dispersive soils cannot be distinguished by appearance or basic physical properties (e.g., Atterberg limits, particle size) from erosion-resistant clays. Since internal erosion often occurs without visible signs, failure may occur suddenly, progressing rapidly from initial cracking or subsidence to catastrophic collapse.
5	What are effective mitigation measures for dispersive soils?	The most reliable measures include removal of dispersive soil, replacement with non-dispersive material, or avoiding its use altogether. As most failures are triggered by water ingress through cracks or openings, additional measures include use of properly designed filter materials, concrete slope protection, and installation of impermeable liners. Chemical stabilization to reduce soil dispersivity is also a viable treatment method.
6	Are there any international design codes or standards for dispersive soils?	No internationally unified design standards exist for dispersive soils.
7	What is the difference between dispersive and collapsible soils?	Dispersive soils chemically disintegrate and disperse in still water due to high exchangeable sodium, whereas collapsible soils typically occur in arid regions and lose structural integrity under moisture due to weak inter-particle bonds.
8	What is the Crumb Test?	A simple visual assessment wherein a cube-shaped specimen (approx. 16 × 6.5 mm) is placed in distilled water to observe particle dispersion. The degree of dispersion is classified into four levels (ASTM D6572).
9	What is the Double Hydrometer Test?	This test involves sedimentation analysis with and without dispersant. The dispersivity ratio (DR) is calculated as the percentage of particles finer than 0.005 mm in the test without dispersant divided by the same in the test with dispersant. Soils with DR $< 15\%$ are classified as non-dispersive; DR $> 50\%$ are considered highly dispersive (ASTM D4221).
10	What is the Pinhole Test?	A direct method for evaluating dispersivity of clayey soils. A cylindrical specimen (30–38 mm diameter, 38 mm height) is prepared, and a 1 mm diameter pinhole is made through it. Distilled water is passed under various heads (50 mm, 180 mm, 380 mm, 1020 mm), and classification is based on turbidity, final hole diameter, and flow rate (ASTM D4647).

D4 LATERITE

No.	Question	Answer
1	What is laterite?	Laterite is a residual soil rich in iron and aluminum oxides, typically exhibiting a reddish-brown color due to the high iron content. It is commonly formed under hot and humid tropical conditions. The term "laterite" lacks a universally accepted definition, and the material occurs in a wide range of forms—from hard, indurated blocks to granular or soft fine-grained soils—with significant variability in physical properties such as density and porosity.
2	In which regions are laterites found?	Laterites are widely distributed across tropical regions, including: Africa: Ghana, Nigeria, Côte d'Ivoire, Cameroon, Republic of the Congo, Angola, Kenya, Uganda, Tanzania Asia: India, Sri Lanka, Thailand, Vietnam, Cambodia, Laos, Malaysia, Indonesia Oceania: Papua New Guinea, Australia South and Central America and the Caribbean: Brazil, Colombia, Venezuela, Mexico, Cuba, Jamaica, Haiti, Dominican Republic
3	Is laterite considered a good-quality material?	Laterite has traditionally been used as a good fill material, especially for embankments. However, it exhibits significant variability in gradation, Atterberg limits, moisture content, compaction characteristics, and mechanical properties. These properties can also change depending on how the material is processed and prepared, which requires careful consideration in its use.
4	What should be considered when using laterite?	While widely used as subgrade and subbase material in road construction, many reported cases of road damage suggest that variability in lateritic soil properties and the lack of standardized evaluation methods may contribute to such failures. Therefore, proper assessment of laterite's geotechnical characteristics and suitability as a construction material is critical.
5	How is laterite identified or evaluated?	There is no universal or standardized method for identifying or classifying all lateritic soils. In many countries, particularly in road engineering, index properties such as California Bearing Ratio (CBR), Plasticity Index (PI), water absorption, abrasion loss, and linear shrinkage are used as evaluation criteria.
6	Is laterite classified as a problematic soil?	Although laterite is typically evaluated using conventional physical and mechanical soil tests, its properties—such as particle size distribution and plasticity—can be significantly influenced by sample preparation procedures. Since the compaction and strength characteristics (e.g., CBR) are also sensitive to test protocols, no standardized method has been universally established for accurate assessment. Therefore, expert judgment, careful planning, and rigorous field and laboratory evaluation are necessary when dealing with lateritic soils.

D5 COLLAPSIBLE SOIL

No.	Question	Answer
1	What are collapsible soils?	Collapsible soils are a type of problematic soil characterized by a structural breakdown of soil particles when subjected to external factors such as moisture infiltration or increased loading. This leads to sudden changes in volume or settlement. Typical types include loess, sandy loams, volcanic ash-derived soils, and alluvial fan or fluvial deposit-derived soils.
2	In which regions are collapsible soils distributed?	Representative collapsible soils such as loess are widely found in: Asia: Loess Plateau in China and Mongolia, Central Asia (Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan) Middle East: Iran, Iraq North America: Central U.S. (prairie regions) Europe: Germany, Eastern Europe – Africa: Egypt, Sudan, Algeria, Morocco, South Africa, Nigeria, Ethiopia, Kenya
3	How are collapsible soils identified?	Evaluation methods include laboratory testing (typically one-dimensional consolidation or loading tests under dry and wet conditions), and in-situ testing such as plate loading tests and cone penetration tests (CPT). However, no standardized international criteria or test protocols exist, and evaluation methods may vary depending on the researcher or region.
4	How do collapsible soils affect construction?	Notable problems caused by collapsible soils include: Large-scale landslides Cracking or deformation in residential structures Cracking, subsidence, and pavement damage in roads Embankment settlements and slope failures in cut-and-fill operations Such failures may occur unexpectedly, triggered by changes in topography due to construction, fluctuations in surface and groundwater levels due to heavy rainfall, dynamic loads from vehicles, or seismic events.
5	What countermeasures can prevent damage caused by collapsible soils?	Since collapsibility is primarily triggered by increased moisture content, it is critical to carefully control drainage in and around affected areas. Engineering countermeasures may include: Soil replacement Surface and subsurface water control measures Ground densification (e.g., dynamic compaction, vibroflotation) Chemical stabilization (e.g., cement treatment) However, there are no universally accepted mitigation methods, and diverse techniques are applied depending on local conditions and engineering practices.

D6 DISTRIBUTION MAP OF PROBLEM SOIL

No.	Question	Answer
1	What is the accuracy of the problematic soil distribution maps provided in the appendix of this handbook? Are there any precautions for their use?	The problematic soil distribution maps in the appendix of this handbook were developed based on the Harmonized World Soil Database (HWSD), incorporating global distribution data for specific types of problematic soils. For certain soil types, national-level data has also been included. These maps are intended to serve as preliminary reference material when initiating development projects. However, they are not of sufficient accuracy to be directly used for planning, design, or construction. It is essential that project stakeholders develop their own detailed distribution maps through on-site reconnaissance, geotechnical investigations, and laboratory testing during the survey phase of each project. These maps should be continuously refined and updated throughout the planning, design, construction, and maintenance phases.

APPENDIX E. CASE STUDIES OF PROBLEM SOIL

Soil Type	Black Cotton Soil (Expansive Soil)		
Country	Ethiopia		
JICA Grant Aid			
Project Title	The Project for Rehabilitation of Trunk Road, Phase Ⅳ		
Damage	Pavement Damage (Confirmed in 2014)	Completion	March 2014 (Phase I), February 2016 (Phase II)

Project Overview

■The project aimed to rehabilitate the deteriorated section of National Road No. 3 between Dejen and Debre Markos in the Amhara Region, part of the corridor connecting Ethiopia's capital Addis Ababa with neighboring Sudan.

Phase I: Dejen – Lumame (29.0 km)

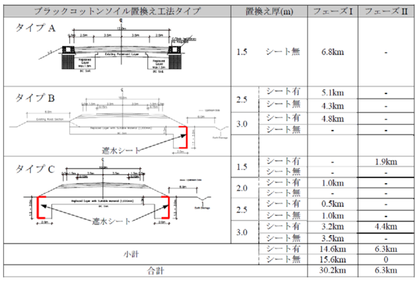
Phase II: Lumame – Debre Markos (39.9 km)

Location

Pavement Damage

Design Stage Measures

■Design Stage Measures
・Replacement with high-quality material
・Combined use of waterproof sheets in areas with poor drainage
・Embankment structure to address inundation



ブラックコットンソイル置換え工法タイプ	置換え厚(m)		フェーズI	フェーズII
タイプ A	1.5	シート無	6.8km	-
タイプ B	2.5	シート有	5.1km	-
		シート無	4.3km	-
	3.0	シート有	4.8km	-
		シート無	-	-
タイプ C	1.5	シート有	-	1.9km
		シート無	-	-
	2.0	シート有	1.0km	-
		シート無	-	-
	2.5	シート有	0.5km	-
		シート無	1.0km	-
	3.0	シート有	3.2km	4.4km
		シート無	3.5km	-
小計		シート有	14.6km	6.3km
		シート無	15.6km	0
合計			30.2km	6.3km

Damage from Problem Soil and Repair Status

■Black cotton soil, a type of expansive soil, is widely distributed in Ethiopia. It is characterized by significant swelling and shrinkage due to changes in moisture content.

■In particular, in the Yetnora area—prone to black cotton soil influence—approximately 600 meters of road surface damage (cracks and unevenness) was observed at the end of 2014.

■In May 2015, before the defect inspection, the contractor performed repairs using overlay (patching) methods.

■In the 2018 ex-post evaluation, further deformation, cracks, and subsidence of the pavement caused by black cotton soil were confirmed at the same location.

■Although no accidents have been reported due to the pavement damage, users have noted a loss of driving comfort.

Measures and Future Challenges

■Local government conducted an investigation into the causes of pavement damage. The results identified the following factors:
・Softening of the subgrade due to moisture
・Clogging of drainage channels
・Use of poor-quality construction materials
・Differential movement between box culverts and the pavement

■Early deterioration of the pavement is most likely due to subgrade settlement caused by the swelling effect of expansive soil. Black cotton soil swells and weakens upon moisture absorption. When such problematic soil is present in the subgrade, it loses bearing capacity and cannot withstand traffic loads.

■Rehabilitation plan: asphalt pavement based on conventional Marshall mix design methods

■To maintain road performance in the long term after rehabilitation, the following challenges must be addressed:
・Further investigation of appropriate countermeasures against black cotton soil
・Improvement of construction quality and proper material selection
・Strengthening of continuous monitoring and maintenance systems

わだち掘れの発生

わだち掘れと亀甲クラックの発生

亀甲クラックと簡易な補修（現地政府）

現地政府による補修状況（破損部分の撤去）

Source: Revised Final Report of the Basic Study on the Approach to Road Development Projects through Financial Cooperation in Africa (Ethiopia, Ghana, Tanzania)

Soil Type	Black Cotton Soil (Expansive Soil)
Country	Ethiopia
Science and Technology Research Partnership for Sustainable Development (SATREPS)	
Project Title	The Project for Development and Operation Model of Plant-derived Soil Additives for Road Disaster Reduction on Problematic Soil
Period	April 2019 – March 2024

Overview

■Background

・In Sub-Saharan Africa, the expansion of road networks contributes to economic development and improvement in welfare and education, while the widespread occurrence of black cotton soil (expansive clay soil) presents significant challenges in road construction and maintenance.

・Expansive soil has the property of expanding when it absorbs moisture and contracting when it dries, causing mud formation and settlement during the rainy season and hardening and heaving during the dry season. Previously, measures involved replacing the top 1-2 meters of roadbed with high-quality soil, but securing quality soil has become more difficult. There is now an increasing need to improve the problematic soils themselves and utilize them as effective ground materials.

■Objective

・To develop plant-derived soil additives and establish a local, sustainable model for improving problematic soils.

※Excerpt from official website of the project

Achievements (as of April 2025)

■Research Topic 1: Soil Improvement with Cellulose-based Additives (Fundamental Research):

・Cellulose and plant-derived powders were tested in black cotton soil, but alone, they did not meet the required CBR 3 standard. Lime mixing was found necessary.

・The additives formed an impermeable layer, potentially stabilizing moisture fluctuations, though this approach may be too conservative for small-scale road designs.

■Research Topic 2: Production Techniques for Cellulose-based Additives from Indigenous Plants (Applied Research):

・Addis Ababa Science and Technology University (AASTU) established stable operations for crushing and powdering, and Ginka University is advancing large-scale processing.

・Sugarcane bagasse showed promising results in water absorption tests and was deemed effective as a soil improvement material. Both Ethiopian and Japanese teams verified the effectiveness through mechanical testing.

■Research Topic 3: Operational Model for Road Disaster Reduction (Social Implementation):

・Road disaster and mitigation measures in South Omo County were assessed, including creating disaster maps using satellite images and local data.

・A large-scale road improvement experiment at Ginka University using cellulose-based additives was conducted, verifying their effectiveness. Feasibility studies for introducing manual construction methods and local soil improvement were also explored.

※Excerpt from FY 2023 Implementation Report

Visit to Addis Ababa Science and Technology University (Ethiopian Researchers) (October 2024)

Addis Ababa Science and Technology University Laboratory

Soil Improvement Materials Used

Source: JICA Study Team

Soil Type	Dispersive Soil (Dragon Hole)		
Country	Cambodia		
JICA Grant Aid			
Project Title	The Project for Rehabilitation of the National Roads Route 6 and 7		
Damage	avement damage (Confirmed in 2004)	Completion	1998年6月

Project Overview

■National Roads No. 6A, 6, and 7 are among Cambodia's most important trunk roads.

The project involved the rehabilitation of roads between Snoulken and Kampong Cham along Routes 6 and 7, aiming to improve transport between the northeastern agricultural region and the capital city.

This contributed to stabilizing Cambodia's social and economic activities.

■Design Stage Measures: As a countermeasure against dispersive soil, cohesive soil lining was applied to protect embankment slopes.

Damages Due to Dispersive Soil

■When embankment or slope material contains dispersive soil, infiltration of water can lead to dissolution, gully erosion, collapse, and formation of features known locally as "Dragon Holes"—vertical shafts or sinkholes formed by tunnel erosion. These phenomena are not typically observed in Japan.

Source: Revised Final Report of the Basic Study on the Approach to Road Development Projects through Financial Cooperation in Africa (Ethiopia, Ghana, Tanzania)

About Dragon Hole

■Dragon Holes are vertical voids in embankments, often 20–50 cm in diameter, formed vertically from the road surface or slope and believed to connect with horizontal tunnels at the bottom of the slope.
Rainwater infiltration causes erosion, forming underground cavities known locally as "Dragon Hole."

■Causes and Mechanism
・These occur regardless of the construction contractor, suggesting the primary cause is the presence of dispersive soil.
・Horizontal cavities form due to dispersive soil; water movement along vertical cracks results in piping and formation of vertical shafts.
・Surface erosion and nearly vertical tunnel erosion are typical damage patterns.

■Features
・Widespread occurrence in flatland road embankments in Cambodia
・Found not only in road embankments but also in levees and paddy ridges
・Typically occurs in embankments inundated during the rainy season, rarely in mountainous regions
・Occurs universally regardless of designer, constructor, or maintenance agency

Source: JICA Study Team

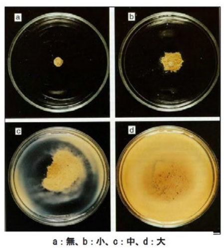
Dragon Holes Observed During the Field Survey in Cambodia (July 2024)

Measures

■In the 2009 JICA technical cooperation project "Project for Strengthening Quality Control in Construction," trial construction for dispersive soil countermeasures was conducted.
・A simple field test for identifying dispersive soil was introduced to allow local engineers to recognize the soil type easily.
・Stabilization of dispersive soil is said to be possible through the addition of calcium-rich materials such as cement or lime.

■Proposed Countermeasures:
・Conduct a simple field test for soil type before construction to determine the presence and degree of dispersiveness.
・Compare the cost-effectiveness between importing good-quality soil and improving with cement additives.

■Effective Construction Conditions for Soil Improvement:
・Additive: Cement
・Mixing Ratio: ≥2.5%
・Mixing Time: 3.3 minutes/m^3 (using backhoe of 0.4–0.6 m^3 capacity)



Criteria for Evaluating the Degree of Dispersibility

Source: JICA Study Team

Simplified Dispersibility Test Conducted During the Field Survey in Cambodia (July 2024)

Soil Type	Laterite		
Country	Laos		
JICA Grant Aid			
Project Title	The Project for Improvement of the National Road Route 9		
Damage	Structural Failure (Confirmed in 2012)	Completion	March 2001 (Phase 1), December 2002 (Phase 2)

Project Overview	Design Stage Measures
■National Road Route 9 traverses the central-southern region of Laos and is a critical arterial road providing sea access for the landlocked country. It also serves as a key segment of the Indochina peninsula's east-west economic corridor, playing an important international role. The project involved the improvement of approximately 53 kilometers of roads and bridges within the 73-kilometer section between Xeno and Muang Phalan. ■Design Stage Measures Cement stabilization was applied at a cement content rate of 3%.	■Pavement Structure in the Basic Design: ・Surface Course Given the frequent passage of overloaded vehicles and the need to prevent water infiltration into the roadbed, an asphalt concrete (AC) type surface was adopted. ・Upper and Lower Subbase Courses To maximize the use of locally sourced materials, the lower subbase was designed with cement-stabilized soil, while the upper subbase used graded crushed stone. Additionally, a bound treated base (BTB) was constructed on top of the graded crushed stone layer to suppress dust generation during construction. Source: Detailed Design Report

Cause Analysis and Measures

Source: Revised Final Report of the Basic Study on the Approach to Road Development Projects through Financial Cooperation in Africa (Ethiopia, Ghana, Tanzania)

■Cause of Damage
The main causes of the damage were overloaded vehicles and deterioration of the cement-stabilized layers. Alligator cracking occurred frequently. It was found that the strength of the existing cement-stabilized lower subbase was significantly lower than expected.

■Measures
The pavement structure in the severely damaged section between Xeno and Muang Phin was reinforced, and the road was upgraded with improved drainage facilities as part of the "National Road Route 9 (East-West Economic Corridor in the Mekong Region) Improvement Project."

■Details of the Rehabilitation:
Asphalt concrete pavement was selected, taking into account the specifications of the existing sections and other rehabilitated roads. Additionally, to reduce costs and consider environmental impacts, in-place recycling methods were applied in some sections, allowing for the reuse of existing road materials.

Method	TNF Method (Ground Improvement Type Direct Foundation Structure)	Company	Takeuchi Construction Co., Ltd. (Mihara City, Hiroshima)
Country	Vietnam		
Soil Type	Soft Ground		
SDGs Business Supporting Survey (JICA Biz)			
Project Title	Project Formation Survey on the TNF Method for Soft Ground Areas Survey for Promoting the TNF Method (Direct Foundation with Ground Improvement) in Soft Soil Regions		
Period	July 2015 – June 2016		

Method Overview

■The TNF (Tender Net Foundation) method integrates foundation, ground improvement layer, and slab to evenly distribute the building's load across the slab and foundation without using piles. The system creates a grid-like ground improvement beneath the building, stabilizing the ground and preventing uneven settlement by supporting the building uniformly. This method also avoids pile uplift and prevents damage to underground equipment and pipes.

■Key Features
・Cost: Low-cost foundation by improving the surface soil layer and using it as a supporting layer, reducing foundation costs by up to 40% compared to concrete piles.
・Construction Period: Around 40% shorter than conventional pile foundations.
・Environment: Unlike traditional methods, no soil replacement is required, reducing environmental load by avoiding river sand procurement and construction waste disposal.

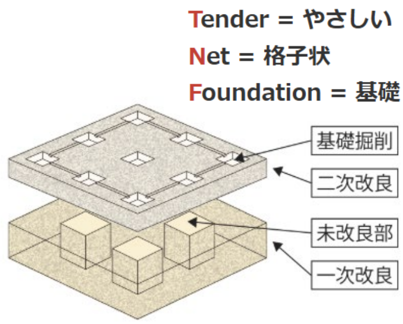


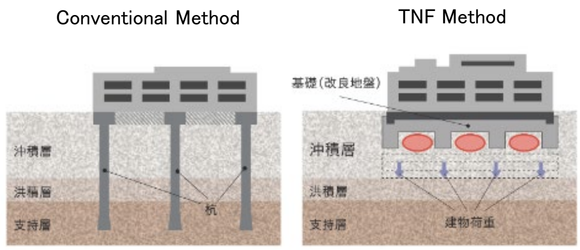
Illustration of TNF Method Construction

Excerpt from company's official website

Objectives and Achievements

■Objective
Conduct investigations necessary for the adoption of the TNF method for building foundations in Vietnam. This includes verifying the method's suitability for local soil, securing government approval, and studying local demand for its widespread use.

■Key Achievements:
・By improving the foundation beneath buildings in a grid pattern, the soil stress is distributed, preventing uneven settlement.
・Design helps improve foundation stability by embedding the surrounding ground into the improvement body.



Foundation (Support Pile) Foundation (TNF Soil Improvement)

Schematic Diagram of TNF Method

Excerpt from company's official website

Current Status and Future Challenges

■Current Status
SATI recognizes the technical superiority and suitability of the TNF method for Vietnam's soft ground, with hopes for future trials and business implementation.

■Future Challenges:
・Changes in construction regulations, permits, and tax policies.
・Maintaining compliance awareness to prevent technological leakage

Excerpt from the Final Report of
SDGs Business Supporting Survey (JICA Biz)

■Issues in Soft Ground Treatment in Vietnam
・Traditional wood piles, though widely used, have durability issues and have caused significant building damage.
・Concrete pile foundations are now common but may fail if soil conditions aren't adequately checked, especially for large or spread-out buildings.
・Problems like uplift can still occur with foundations that don't settle properly, and sand replacement methods present issues with waste disposal and river environmental impact.
・While private sector projects are embracing new technologies, the introduction of new methods in public projects is constrained by budget limitations.

Method	EcoGeoDrain SPD Method	Company	Chikami Mirtec Co., Ltd. (Kochi City, Kochi)
Country	Indonesia		
Sotil Type	Soft Ground		

SDGs Business Supporting Survey (JICA Biz)

Project Title	SDGs Business Model Formulation Survey with the Private Sector for Soft Ground Stabilization by Eco Geo-Drain SPD Method in Indonesia
Period	February 2022 - February 2023

Method Overview

■The EcoGeoDrain SPD (Suction Plastic Board Drain) method involves installing plastic drains vertically in soft ground, combined with horizontal drains, and sealing the area with a waterproof sheet. A vacuum pump is then used to promote drainage, improving the soil. The method addresses material shortages for embankment and drainage, which have caused delays in conventional methods. The proposed product uses biodegradable plastic made from plant-based materials, which decompose into water and carbon dioxide after use, preventing future interference with underground construction.

■Key Features
・Cost: The EcoGeoDrain SPD method reduces costs by about 17.5% compared to traditional embankment methods.
・Construction Period: The method shortens construction time by approximately 35.8% due to the elimination of embankment transportation and removal.
・Environment: By using plant-based biodegradable plastic for the drains, the method prevents the potential for microplastic contamination and future hindrance to underground works like shield tunneling.


Illustration of SPD Method

Excerpt from the Final Report of
SDGs Business Supporting Survey (JICA Biz)

Objectives and Achievements

■Objectives
To understand existing guidelines, soil conditions, and the current use of consolidation methods in Indonesia, as well as to evaluate the feasibility of biodegradable drains and promote understanding among local government stakeholders.

■Achievements
・The EcoGeoDrain SPD method reduces costs by 17.5% and shortens construction time by 35.8% compared to conventional methods.
・The use of biodegradable plastic drains prevents future environmental risks like microplastic contamination and avoids issues for future underground construction.

Excerpt from the Final Report of
SDGs Business Supporting Survey (JICA Biz)

Current Status and Future Challenges

■Current Status
While soft ground in Indonesia is often a combination of expansive clay and weak soil, which requires more than just clay consolidation for effective improvement, a collaboration with Dr. Hasbi of Bandung Institute of Technology has been established to combine the EcoGeoDrain SPD method with expansive soil treatment.

■Business Development Insights
There is growing demand for environmentally friendly ground improvement methods, especially in Indonesia's coastal economic zones and new port developments, where 10% of the country's land is soft ground.
・Vacuum consolidation prevents construction failures due to drainage issues.
・Biodegradable drains help mitigate concerns over marine plastic pollution and underground construction obstacles.

■Future Challenges
・Biodegradability Testing: Testing the biodegradability and water flow maintenance of the drains in Indonesia with Bandung Institute of Technology.

・Soil Data Collection: Gathering soil data from potential sites to confirm the applicability of the technology.

・Material Supply and Demand Information: Understanding the availability of soil and sand in targeted areas to demonstrate the advantages of the proposed method.

・Stakeholder Understanding: Promoting awareness and understanding of biodegradable drain materials among relevant Indonesian agencies.

・Data Gaps: Additional soil testing in Indonesia is needed to assess the suitability of EcoGeoDrain SPD and PVD methods.

Product	Porous Concrete Products	Company	Hokkaido Poracon Co., Ltd. (Sapporo City, Hokkaido)
Country	Indonesia		
Soil Type	Expansive Soil and Soft Ground		
SDGs Business Supporting Survey (JICA Biz)			
Project Title	SDGs Business Validation Survey for Introducing Porous Concrete Products for the Mitigation of Inundation Damage due to Rainwater in Indonesia		
Period	August 2024 – March 2026		
Project Title	SDGs Business Model Formulation Survey with the Private sector for Introducing Porous Concrete Products for Preventing Infrastructure Damage due to Expansive and Soft Soil in Indonesia		
Period	March 2022 – December 2023		
Project Title	Survey on Introducing Porous Concrete Products for Prevention of Damage to Infrastructure by Expansive Clays(SME Partnership Promotion)		
Period	February 2019 – November 2019		

Product Overview

■Porous concrete products are made from special concrete with a continuous porous structure, characterized by water permeability, infiltration capacity, vegetation compatibility, sound absorption, and purification effects.
■For flood and inundation control, two main construction methods are used: the Infiltration Method, which allows rainwater to infiltrate into the ground, and the Drainage Method, which collects and discharges rainwater retained in the ground—particularly useful for soft ground conditions.
■In the context of infrastructure damage caused by expansive soils in Indonesia, the Drainage Method is expected to be effective by rapidly collecting and draining rainwater that has entered the ground.

Excerpt from the Final Report of SDGs Business Supporting Survey (JICA Biz)

Objectives and Applications

■Objectives
By introducing porous concrete products in areas with expansive soils and soft ground, the aim is to suppress ground expansion and shrinkage, reduce damage to economic and transportation infrastructure built on such ground, and promote the widespread use and commercialization of the products and methods.

■Applications in Infrastructure (e.g., Roads)
・Drainage pipes and U-shaped gutters made of porous concrete are installed beside or beneath roads built on expansive soils to promptly collect and discharge rainwater that infiltrates road surfaces or subgrades, thereby suppressing soil expansion and preventing pavement damage.
・In slope areas of roads constructed on expansive soils, stepwise installation of porous concrete products at the toe of each slope section helps regulate groundwater levels and prevent slope failures caused by soil expansion.

■Applications for Rainwater Runoff Control
・Infiltration methods are used to mitigate rainwater runoff.
・In Jakarta and other areas, infiltration wells are increasingly being adopted as part of flood countermeasures.
・Infiltration wells are being introduced for public institutions, while infiltration pits are more common among private enterprises. However, functional implementation based on rainwater runoff calculations considering rainfall and soil type is still limited.

Current Status, Business Insights, and Future Challenges

■Current Status
The SDGs Business Validation Survey for Introducing Porous Concrete Products for the Mitigation of Inundation Damage due to Rainwater in Indonesia is currently underway. Based on the previous feasibility survey, which confirmed the need and local compatibility of porous concrete products, the current phase involves verifying local production feasibility, promoting appropriate utilization methods, establishing a production system, and developing sales channels.

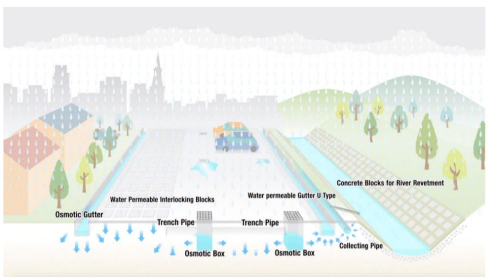


Fig.4 Applications of Porous Concrete products

■Business Insights for Market Development
The usefulness of porous concrete products has been demonstrated, and the spread of construction methods for expansive soil and soft ground countermeasures is expected to promote the development of transportation infrastructure in Indonesia. It may also lead to the establishment of technical guidelines and design standards for highway maintenance. In addition, mitigating damage from expansive soils in industrial zones near Jakarta could contribute to improving the foreign investment environment.

■Future Challenges
・Institutional Compatibility: Legal systems for rainwater infiltration facilities are underdeveloped, posing risks of improper implementation.
・Compatibility with Local Infrastructure: Challenges include difficulty in locally procuring production equipment, sourcing raw materials, and ensuring worksite safety.
・Importance of Local Partners: It is essential to secure pilot construction sites and gain the cooperation of local developers and design firms.

Method	Middle layer Soil Mixing Method	Company	YBM Co., Ltd. (Saga)
Country	Indonesia		
Soil Type	Soft Ground		

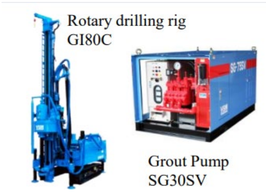
SDGs Business Supporting Survey (JICA Biz)

Project Title	Verification Survey with the Private Sector for Disseminating Japanese technologies for Introduction of the Ground Improvement with the Middle layer Soil Mixing Method for Development of Transport Infrastructure
Period	December 2018 – January 2023
Project Title	Feasibility Survey for the support of development for transport infrastructure through soil improvement with the Interlayer Mixing Method
Period	May 2016 – May 2017

Method Overview

■The Middle Layer Soil Mixing Method is a ground improvement technique not yet applied in Indonesia. It strengthens soft ground by mixing stabilizing agents such as cement or lime with in-situ soil from the surface to a designated depth, forming columnar or mass-treated zones to prevent settlement and sliding failures.

■This method creates improved columns (treated piles) within the ground by mixing cement or lime, enhancing overall soil stability. The solidified columns exhibit low compressibility and minimal settlement under load, with rapid development of improvement effects. While strength verification through laboratory mix design and unconfined compression testing is required, the method is applicable to various soil types, including clayey, sandy, and organic soils.



Excerpt from the Final Report of SDGs Business Supporting Survey (JICA Biz)

Objectives and Achievements

■Objectives

To introduce the Middle Layer Soil Mixing Method—a new ground improvement technology with no prior implementation in Indonesia—to mitigate ground settlement and seismic damage in soft ground areas. The project also aims to establish a market for high-quality, precisely operable equipment suited for this method.

■Achievements

・Unlike the vertical drain method commonly used in Indonesia, which is ineffective when sand layers underlie organic soils, the Middle Layer Soil Mixing Method can be applied in such conditions. This expands the applicability of ground improvement to complex soil profiles and offers a solution to previously unresolved settlement issues.

・The method enables controlled ground strength and formation of high-strength, low-variance improved columns. It is suitable for confined construction sites and offers advantages over existing methods such as vertical drains and compaction piles. It can also be applied for temporary earth-retaining walls, liquefaction countermeasures, and foundations of civil and building structures. The method is expected to gain wider adoption, particularly in soft ground regions like Sumatra and Kalimantan.

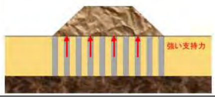
Method	Middle layer Soil Mixing Method
Schematic Diagram	
Overview	・Make cement column in soft soil to gain strength, and build structures.
Merit	・High effect of improvement ・Short construction period ・Less effect or damage to surrounding areas ・Low labor cost and other expenses by short construction period.
Strength	・Able to adjust to the precisely required strength certainly by doing laboratory mixing test before actual work

Figure 3: Characteristics of Middle layer Soil Mixing Method

Current Status, Business Insights, and Future Challenges

■Current Status

In January 2024, Indonesia's Ministry of Public Works approved technical guidelines for the Middle Layer Soil Mixing Method, enabling its use in public projects. The method has already been adopted for ground stabilization at an automotive test course in Bekasi, near Jakarta. Outreach continues toward general contractors, consultants, and ground improvement firms to promote wider adoption.

Source: https://www.jica.go.jp/activities/schemes/priv_partner/sdgs/2024/20241118_02.html)

■Future Challenges

To increase recognition, further pilot applications are needed to build a solid track record. Collaboration with Hutama Karya is ongoing to explore field implementation. Additionally, handling used equipment is under consideration, as early-stage market demand tends to favor affordable, second-hand machinery.

■Business Insights for Market Development

The method facilitates ground improvement in previously unsuitable conditions, contributing to shorter construction times, fewer defects, and settlement control. It offers major socioeconomic benefits through improved infrastructure. Its quick-effectiveness suits private sector projects, particularly expressways in soft ground areas. The compact equipment also allows construction in confined urban sites, meeting growing demands in high-density areas.

Product	STEIN	Company	SPEC Co., Ltd. (Tokyo)
Country	Cambodia, Sri Lanka, Kenya, Nigeria, Ghana		
Soil Type	Capable of adapting to nearly all soil types by adjusting the mixing ratio.		
SDGs Business Supporting Survey (JICA Biz)			
Project Title	Verification Survey with the Private Sector for Disseminating Japanese Technologies for Development of Irrigation and Agricultural/Rural Roads utilizing the STEIN soil hardener		
Period	March 2019 – January 2023		
Project Title	Feasibility Survey for the Development of Irrigation and Agricultural Facilities by the STEIN Soil Hardening		
Period	July 2016 – July 2017		
Other			
・Reiwa 5 Fiscal Year J-Partnership Support: Road and pond construction projects addressing the Black Cotton Soil problem in Kenya, using Soil Hardening Agent STEIN (June 2023)			
・Ministry of Foreign Affairs Decarbonization Technology Overseas Deployment Initiative: Selected as a decarbonization product (March 2023)			

Product Overview

■STEIN is a powdered soil hardener, produced by mixing 5% of the STEIN element (using ordinary cement as a base and pre-mixed with 27 kinds of harmless inorganic additives) and 95% of ordinary Portland cement.

■STEIN is an environmentally harmless soil hardener made of inorganic powder, developed in Japan in 1975. It is mixed with the site soil at about 10% by weight, and after optimal moisture adjustment and compaction, it hardens in a short period to create strong structures.

■STEIN Method: Compared to asphalt paving, the construction cost is 40-60% lower. It excels in strength and water resistance, minimizing issues like cracking and water pooling. The method allows for easy and cost-effective construction of irrigation facilities and roads with high durability. Furthermore, it has minimal environmental impact and requires almost no maintenance, reducing running costs.

STEIN

Excerpt from the Final Report of SDGs Business Supporting Survey (JICA Biz)

Objectives and Applications

■Achievements

・In the SDGs Business Supporting Survey (JICA Biz), STEIN's hardness met the planned values, and no issues were observed in the road functionality based on visual evaluation. However, minor erosion, wear, cracking, and subsidence were observed, particularly at the road edges where heavy vehicles caused gouging. Subsidence was confirmed in both treated and untreated sections, likely due to the soft ground below the subgrade and issues in the subgrade layer.

■Applications

The main feature of construction using STEIN is that it simplifies the process by using site soil, reducing both the construction period and costs. The process is completed within 4 hours after mixing soil with STEIN, and roads are passable within 24 hours. Target strength is achieved in about one week, with resistance to weathering, erosion, and thermal deformation. The expected service life is up to 45 years, with almost no maintenance required. This method is expected to be widely adopted for roads, sidewalks, waterways, ponds, etc.

⑨施工範囲の区分け (a) ⑩STEIN の設置(b)

⑪STEIN 敷き均し (b) ⑫バックホウによる STEIN 混合 (b)

Business Insights and Future Challenges

■Business Insights

・In the Cambodian market, STEIN has been confirmed to have sufficient price competitiveness. However, private real estate developers tend to focus on the appearance of the surface, so strategies like painting may be required to cater to different clients. Additionally, since STEIN is a "construction-included product," securing reliable certified contractors and close collaboration will be key to business success.

・During the project period, STEIN manufacturing equipment was transferred to MOWRAM, and technical transfer was conducted through training for MOWRAM, PDWRAM staff, and construction contractors. MOWRAM has shown intent to continue supporting market expansion, and STEIN manufacturing will take place in Takeo, where the equipment has been installed. The STEIN elements will be supplied locally to certified contractors.

■Future Challenges

・Ensuring Continuity of Technical Transfer: To avoid gaps in knowledge transfer due to personnel changes at MOWRAM and PDWRAM, technical updates and knowledge retention will continue even after the project period ends.

・Addressing Aesthetic Challenges: Since the mixed soil retains its natural color, it will be important to clearly specify its characteristics in design and construction manuals and thoroughly explain it before accepting orders. For private developers in Cambodia, proposals for enhancing aesthetics, such as painting, will be made.

・Countermeasures for Weak Subgrade: In Cambodia, weak subgrade is an issue. Therefore, during the planning of the pavement, careful consideration must be given to the design of the subgrade, subbase, and foundation to ensure that STEIN can be applied effectively, and coordination with the contractor will be necessary.

Product	Drainage sheet "Geostream"	Company	Tanaka Co., Ltd. (Izumiootsu City, Osaka)
Country	Cambodia		
Soil Type	Dispersive Soil (Dragon Holes)		
SDGs Business Supporting Survey (JICA Biz)			
Project Title	SDGs Business Validation Survey for Installation of Drainage Sheet to Prevent Rainfall-Induced Road Collapse in Cambodia		
Period	July 2023 – October 2024		
Project Title	SDGs Business Model Formulation Survey with the Private Sector for Drainage Sheet with a Function to Eliminate Rainfall Infiltration Water Causing Existing Road Collapse in Cambodia Road Network		
Period	March 2020 – December 2022		

Product Overview

■Drainage sheet "Geostream" is a type of geotextile installed between the subbase and subgrade of road shoulders or beneath the protective soil on road embankments. It functions to separate soil and water and provides drainage.

■Main Features:
・Equipped with ground reinforcement functionality, it reduces long-term damage to road shoulders caused by rainfall when installed along the shoulders.
・Made from synthetic fiber, it is highly durable and cost-effective, requiring no maintenance in principle.
・Lightweight and requires no special techniques for installation, making it easy to introduce and adopt.

Tanaka Product:Geostream

Excerpt from the Final Report of
SDGs Business Supporting Survey (JICA Biz)

Objectives and Achievements

■Objectives
In Cambodia, road infrastructure frequently suffers from collapses and embankment failures due to rainfall infiltration, which undermines road safety and durability. The introduction of GeoStream aims to solve these issues, reduce road maintenance costs, and improve safety.

■Achievements
In the model formulation survey, the effectiveness of a three-layer slope-type structure as a countermeasure for dragon holes on embankments was studied. It was confirmed that one of the main causes of dragon holes is rainwater infiltration from road shoulders. Accordingly, the business validation survey employed a two-layer shoulder-type GeoStream to prevent rainwater infiltration from road shoulders.
This shoulder-type GeoStream consists of a 3mm polyester short fiber nonwoven fabric on the upper layer and a 0.5mm polyester long fiber nonwoven fabric on the lower layer. The upper layer provides drainage, while the lower layer provides reinforcement, suppressing water infiltration into the ground and reducing crack formation.

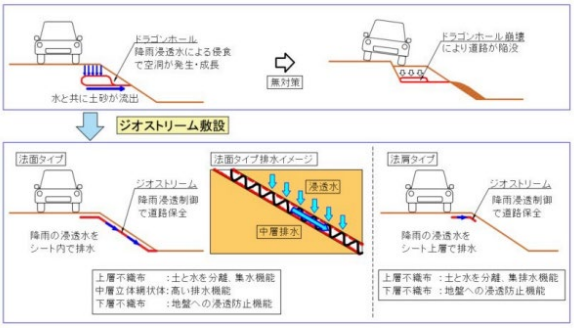
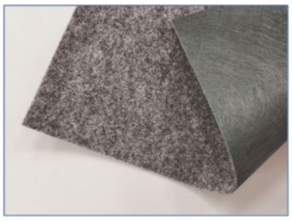


Image of Geostream

Current Status, Business Insights, and Future Challenges

■Current Status
・In February 2024, as part of the above project and with full cooperation from the Ministry of Public Works and Transport (MPWT), trial road repair works using the drainage sheet "GeoStream" were carried out at three sites on national roads in Cambodia.
・Monitoring surveys conducted in March and May (commissioned to Aikame Co., Ltd.) confirmed that ground bearing capacity was maintained at the construction sites.
・A site visit during the rainy season in July visually confirmed the drainage effect of GeoStream during rainfall.



■Insights for Business Development and Future Challenges
・Difficulty in securing budget for GeoStream
When MPWT identifies embankment damage, it is difficult to determine the appropriate timing and criteria for using the product, making it hard to allocate budget.

・Insufficient monitoring results make it hard to explain effectiveness
The causes of surface and embankment damage after the rainy season remain unclear, delaying the verification of GeoStream's appropriateness.

・Lack of understanding of life cycle cost (LCC)
The Ministry of Economy and Finance (MEF) does not fully understand the LCC concept, favoring low-cost products with shorter lifespans.

・Risks in selecting business partners, suppliers, and distributors
Some candidate companies lack sufficient technical capability, posing risks in partnerships, procurement, and distribution.

APPENDIX F. LIST OF SYMBOLS

Symbol	Unit	Synonyms	Description
Ac	-		Activity (Clay Activity)
Ar	-		Aspect ratio
AI		P/PET	Aridity Index
B			Hardin's breakage index
B10	-		Lee et al.'s breakage index
Bg	-		Degree of breakage (Lee et al.)
BM	%	Br	Particle breakage ratio (Marsal)
c	kPa, kN/m2		Cohesion
CB	-		Crushing index
CBR	%		California Bearing Ratio
CC	%		Clay content / Colloid content (e.g., <5μm in Japan)
CEAc	-		Cation Exchange Activity Coefficient
CEC	meq/100g cmol/kg		Cation Exchange Capacity
Cc	-		Compression Index
COLE	cm cm-1		Coefficient of Linear Extensibility
COLEWS	cm cm-1		COLE under saturated conditions
Cm	-		Conversion factor
CROSS	-		Structural stability cation ratio
Cp			Degree of collapsibility
CRR			Cyclic Resistance Ratio (Liquefaction potential)
Cs	-		Swell Index
CSR			Shear stress ratio
cv	s/m		Coefficient of consolidation
Dc	%	D	Degree of compaction
DFS	%	FSI	Free Swell Index
DR	%		Dispersion Ratio
Dr	%		Relative Density
Ec	kN/m2		Elastic modulus during collapse
EC	dS/m		Electrical conductivity
EC1.5	dS/m		EC of 1:5 soil-water mixture
ECe	dS/m		EC of soil saturation extract
ECw	dS/m		EC of irrigation water
ED	kN/m2		Elastic modulus (dry)
EI	%		Expansion Index
eLL	-		Void ratio at liquid limit
emax	-		Maximum void ratio
emin	-		Minimum void ratio
eN	-		Natural void ratio
ESI	-		Electrochemical Stability Index
ESP	%		Exchangeable Sodium Percentage
Ew	kN/m2		Elastic modulus (wet) after collapse
Fc	%		Fines content (<0.075mm)
fs	kPa, kN/m2		CPT sleeve friction
Gs	-		Specific gravity of soil solids
Ic	-		Normalized soil behavior index (CPT)
ICZ			ICZ = (hz - hCZ)/h1
Ip	%	PI	Plasticity Index
Is	%	IS	Shrinkage Index = PL - SL
K	%		Settlement coefficient

Symbol	Unit	Synonyms	Description
K0	-		Coefficient of earth pressure at rest
KL			KL = [(wn/Sr) - PL]/Ip
LL	%	wL	Liquid limit
LS	%	LS	Linear shrinkage
M			Mackintosh Index
MBV	%	VB	Methylene blue adsorption
MMc	%		Montmorillonite content
N	-		Standard Penetration Test (SPT) N-value
P/ET	-	AI	Precipitation/Evapotranspiration ratio
PI	%	Ip	Plasticity Index = LL - PL
PL	%	wp	Plastic limit
ps	kPa, kN/m2		Swelling pressure
qc	kPa, kN/m2		CPT cone tip resistance
qt	kPa, kN/m2		Corrected cone resistance
qu	kPa, kN/m2		Unconfined compressive strength
PVC	kPa, kN/m2		Potential Volume Change
Rc	-		Roundness index
SAMC	%		Swelling active mineral content
SAR	-		Sodium Adsorption Ratio
SBP	%		Saturation by Biopolymer
S.I.	-		Particle breakage index
SL	%	ws	Shrinkage Limit
Sp	%		Swell potential
SSA	m2/g		Specific Surface Area
Sr	%		Degree of saturation
TDS	mg/L		Total Dissolved Solids
TP	mg/L		Total Phosphorus
u	kPa, kN/m2		Pore water pressure
VB	%		Methylene blue value
Vd	ml		Volume of sample in distilled water
Vk	ml		Volume of sample in kerosene
Vp	Km/s		Primary (P) wave velocity
wn	%	w0	Natural water content
wL	%	LL	Liquid limit
wp	%	PL	Plastic limit
ws	%	SL	Shrinkage limit
ΔFc	%		Increase in fines content
△S	mm2		Change in surface area
ε_S	%		Swell strain
σ'_{cv}	kPa, kN/m2		Swelling pressure (consolidation)
σ''_{cv}	kPa, kN/m2		Swelling pressure (constant volume)
ϕ	deg		Internal friction angle
ρd	g/cm3		Dry density
ρdmax	g/cm3		Maximum dry density
ρdmin	g/cm3		Minimum dry density

APPENDIX G. LIST OF ABBREVIATIONS

Abbreviation	English Name
ABI	Association of British Insurers
ACPA	American Concrete Pavement Association
AS	Acid-Soluble Sulfates
ASTM	American Society for Testing and Materials
BCS	Black cotton soil
BG	Butylene Glycol
BG	Beta-Glucan
BS	British Standards
BSP	Base Saturation Percentage
CEAc	Cation Exchange Activity Coefficient
CEC	Cation Exchange Capacity
CAGE	Casagrande’s (Atterberg) Expansion Group Evaluation
COLE	Coefficient of Linear Extensibility
CPT	Cone penetration test
Cz	Carbonate zone
DEM	Discrete Element Method
DTA	Differential Thermal Analysis
EC	Electrical Conductivity
ECe	Electrical Conductivity of Saturation Extract
ECw	Electrical Conductivity of Water
EPS	Extracellular Polymeric Substances
ESI	Electrochemical Stability Index
ESP	Exchangeable Sodium Percentage
EU	European Union
EXD	Energy Dispersive X-ray Spectroscopy
FAO	Food and Agriculture Organization
FDA	Food and Drug Administration
ICOLD	International Commission on Large Dams
HWSD	Harmonized World Soil Database
IIASA	International Institute for Applied Systems Analysis
IS	Indian Standards
ISO	International Organization for Standardization
ISRIC	International Soil Reference and Information Centre
IUSS	International Union of Soil Sciences
ISC	International Science Council
JGS	Japanese Geotechnical Society
JIS	Japanese Industrial Standards
LIG	Lignin
MCV	Modified California Value
MICP	Microbially Induced Calcium Carbonate Precipitation
MS	Monosulfide
NRCS	Natural Resources Conservation Service
PS	palaeosols
RSG	Reference Soil Group
SAMC	Swelling Active Mineral Content
SAR	Sodium Adsorption Ratio
SBP	Sugar-Based Polymer
SBP	Saturation of Biopolymer in Pore
SEM	canning Electron Microscope
SPT	Standard penetration test

Abbreviation	English Name
SPP	Sulfonated Petroleum Products
SSA	Specific Surface Area
TDS	Total Dissolved Solids
TP	Total Phosphorus
TRS	Total Recoverable Sulfates
UCS	Unconfined compression strength
USBR	United States Bureau of Reclamation
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation
WCSS	World Congress of Soil Science
WRB	World Reference Base for Soil Resources
WS	Water-Soluble Sulfates
XRD	X-ray Diffraction
XRF	X-ray Fluorescence

APPENDIX H. REFERENCES

This list contains references collected during the preparation of the handbook. Although not all of them are directly cited in the text, they may be useful for further literature review.

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