Worldwide

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

## Final Report Summary

May 2025

Japan International Cooperation Agency (JICA)

Nippon Koei Co., Ltd.

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Table of Contents

# CHAPTER 1. GENERAL

## 1.1 BACKGROUND OF THE STUDY

ODA projects, including grant aid projects, are implemented in various regions around the world. Within these projects, there are cases where problem soils with unique behaviors are encountered among the soil materials used for foundations and construction materials of the targeted areas.

For instance, expansive soils which swell in response to changes in moisture content have been associated with several serious issues such as significant damage to completed road pavements due to the swelling of black cotton soil in roadbed embankments, collapses caused by the expansion of soil on shallow-cut slopes due to repeated wetting and drying of the soil, and damage to small-scale concrete structures such as drainage works resulting from swelling pressure exerted by backfill materials. In the case of dispersive soils and laterite, they have led to problems such as large-scale surface subsidence, the formation of "dragon holes" on embankment surfaces, severe damage to earthworks slopes, and slope instability.

Since such problem soils are not common in Japan, stakeholders and engineers involved in ODA projects tend to have limited experience and knowledge. They may overlook the presence of problem soils during the design phase, causing plans failing to include appropriate measures. Furthermore, problem soils may not be handled appropriately during construction. As a result, issues may arise, such as unexpected design changes and significant extensions to construction schedules due to unexpected emergence of problem soils during construction, significant functional impairments after completion and commencement of public use, and high repair costs. Especially in grant-aid projects, these issues lead to the project cost exceeding the cabinet-approved amount or construction periods exceeding the agreed schedules, significantly impacting the smooth progress of the project.

Japan has extensive experience in dealing with thickly deposited alluvial soils, soft ground, and problem soils like peat and silty soil. Through repeated trials, Japan has developed excellent knowledge and techniques for ground improvement, stabilization of structures through slope protection, and construction considerations to reduce risks. However, these valuable technologies are not necessarily deployed in other countries, limiting Japan's international presence.

## 1.2 OBJECTIVES

Based on the above background, the objective of this study is to ensure the smooth implementation of ODA projects. The following four points are the aims of the study:

- To create technical materials that will aid in raising awareness and planning countermeasures during the planning stages of future projects, specifically for the problem soils encountered in overseas construction projects.
- To investigate and organize appropriate countermeasures for soil improvement techniques for unsuitable soil materials, slope treatment techniques, and other responses, through literature research and meetings with relevant organizations.
- To compile the above results into a manual for countermeasures against problem soils.
- To demonstrate Japan's comparative advantage in ground improvement technology and contribute to the formation of projects that promote "quality infrastructure investment."

## 1.3 Scope of Problem Soil

The scope of problem soils targeted in this study is as follows:

(1) Soils known as problem soil that exhibit expansive or dispersive properties.

(2) Soil materials derived from coral or other locally dominant soils in regions where securing alternative materials is difficult despite their unsuitability for construction works.

(3) Soils such as laterite found in tropical regions, for which standardized geotechnical evaluations have not been established when used as improved soils or embankment fill.

(4) Soft ground or organic soil serving as roadbed and embankment for roads and other infrastructure constructed in low-lying wetland areas.

## 1.4 Outline of This Report

This report is organized in consideration of the stages of construction projects. Chapters 1 through 5 present the overview of the study, existing literature and case studies related to problem soils, findings of research on Japanese countermeasures, and results of overseas field surveys. From Chapter 6 onward, the focus is on the creation of the handbook and countermeasures for problem soils.

- Chapter 1: General
- Chapter 2: About Problem Soil
- Chapter 3: Case Studies and Analysis of Problem Soil in ODA Projects
- Chapter 4: Japan's Measures for Problem Soil, Ground Reinforcement Technique and Slope Treatment Technique
- Chapter 5: Field Survey (Overseas Survey)
- Chapter 6: Preparation of Handbook for Problem Soil Measures
- Chapter 7: Problem Soil Measures

# CHAPTER 2. ABOUT PROBLEM SOIL

## 2.1 DEFINITION OF PROBLEM SOILS AND THE BACKGROUND

The Japanese Geotechnical Society defines "Problem Soil" as soil which presents difficulties in investigation, design, or construction when using conventional methods. While the term "unusual soil" refers to soil that are uncommon or atypical, "problem soil" specifically denotes soil which causes engineering challenges. The term "problematic soil" is also widely used in academic literature to describe soils that may adversely affect structural performance or construction processes.

Problem soil originated from Problem Soil Zone Disaster Prevention and Promotion Temporary Measures Act enacted in 1952 in Japan. Initially referring to volcanic ejecta and weathered rock, it now encompasses all soils that may cause engineering problems.

## 2.2 FORMATION FACTORS OF SOIL

The academic foundation of soil science was established by Vasily Dokuchaev in the 19th century, who showed that soil variations are closely linked to topography, climate, and parent material, presenting soil as a dynamic entity shaped by multiple natural factors.

In the 20th century, Hans Jenny proposed that soil formation can be expressed as a function of five state factors:

Soil = f (climate, organisms, topography, parent material, time)

This model indicates that soil properties are the result of the natural environment’s changes over time, with each factor independently and interactively affecting the soil's physical and chemical properties and distribution.

- Climate: Affects weathering, organic matter decomposition, and water movement.
- Organisms: Contribute to organic layer formation, mineral breakdown, and soil structure changes.
- Topography: Affects drainage, infiltration and erosion.
- Parent Material: The base material of soil (rock, sediment, organic matter).
- Time: Governs the cycles of soil development, maturity, and degradation.

## 2.3 SOIL FORMATION PROCESSES

**(1) Weathering is the process by which solid rocks and sediments are broken down or altered into soil materials, serving as the starting point of all soil formation processes.**

- Physical weathering: Breakdown by temperature changes, freezing, and expansion.
- Chemical weathering: Alteration through reactions with water or acids.
- Biological weathering: Decomposition by plant roots and microorganisms.

**(2) Processes in Humid Conditions:**

- Leaching: Removal of soluble substances by water.
- Clay translocation: Movement of clay minerals by water.
- Clay destruction: Decomposition of clay minerals due to base ion loss.

**(3) Processes in Humid Tropical Climates:**

- Formation of highly weathered soils with iron-rich layers.
- Concretion Formation: Accumulation of iron and manganese oxides.
- Humus Accumulation: Organic matter from decomposed plant material.
- Oxidation-Reduction Reactions: Oxidation and reduction of metal elements like iron and manganese.
- Surface Weathering: Changes in upper soil layers due to climate and biological activity.

## 2.4 CLASSIFICATION OF PROBLEM SOIL

Problem soils do not have a universally established classification system. As a practice for this study, soils are classified into two major groups: soils with physical properties and those with chemical properties that are of engineering concern, and other characteristic soils that pose engineering challenges.

- Physical properties: expansive soil, dispersive soil, erosive soil, collapsible soil, crushable soil, soluble ground, and soft ground.
- Chemical properties: saline soils, sodic soils, sulfates soils, sulfides soils, carbonate soil, and calcareous soil.
- Others: laterite, volcanic ash soils, sand rich in mica, and glacial sediment.

For further detailed information and figures, please refer to "Handbook for Problematic Soil Measures" for this project.

# CHAPTER 3. CASE STUDIES AND ANALYSIS OF PROBLEM SOIL IN ODA PROJECTS

## 3.1 OVERVIEW OF ODA PROJECTS RELATED TO PROBLEM SOIL

In this project, literature review and interviews were conducted focusing on ODA projects implemented by JICA in the transportation sector, specifically those related to road and bridge infrastructure development, including both grant and loan aid projects, as well as technical cooperation projects.

Based on interviews with project stakeholders, the identified cases have been summarized by country and are presented below.

Table 3.1.1 Status of interviews with ODA project stakeholders

| Country | Experience with Problem Soil |
|---|---|
| ***Southeast Asia*** | |
| Cambodia | There are cases involving expansive soils and dispersive soils in irrigation projects. In road construction projects, dispersive soil was distributed in the surrounding areas, so dispersive soil was selected during material surveys and measures were taken to not use it. |
| Laos | Laterite was used as embankment material, and erosion was prevented by slope protection and vegetation. |
| Indonesia | Expansive soils were encountered and became problematic in various construction projects such as airport and land development. |
| Thailand | Dispersive soils were encountered in land development (cutting) projects. |
| Philippines | There are cases where volcanic ash soil materials have been improved. |
| ***South Asia*** | |
| Bangladesh | No cases of encountering problem soil were identified according to the interviews with ODA project stakeholders. |
| India | There are cases of encountering expansive soils in railway projects and corresponding measures. |
| ***Central Asia*** | |
| Kyrgyzstan | No cases of encountering problem soil were identified according to the interviews with ODA project stakeholders. |
| Tajikistan | Local soil materials were found to be good, and no cases of encountering problem soil were identified. |
| ***West Africa*** | |
| Ghana | Laterite was used as embankment material, and slope protection measures were implemented. Vegetation tends to be difficult to establish. |
| Guinea | Laterite was used as embankment material, and slope protection measures were implemented. Vegetation tends to be difficult to establish. |
| Liberia | No cases of encountering problem soil were identified according to the interviews with ODA project stakeholders. |
| Côte d'Ivoire | No cases of encountering problem soil were identified according to the interviews with ODA project stakeholders. |
| Burkina Faso | Laterite was used as embankment material, and slope protection measures were implemented. |
| ***East Africa*** | |
| Ethiopia | There were cases of road damage caused by encounters with black cotton soil. |
| Tanzania | No cases of encountering problem soil were identified according to the interviews with ODA project stakeholders. |
| Kenya | There is a case where black cotton soil was encountered during a road construction project, requiring large-scale replacement, and the design changes took considerable time. |
| Mozambique | No cases of encountering problem soil were identified according to the interviews with ODA project stakeholders. |

| Country | Experience with Problem Soil |
|---|---|
| Zimbabwe | No cases of encountering problem soil were identified according to the interviews with ODA project stakeholders. |
| Madagascar | No cases of encountering problem soil were identified according to the interviews with ODA project stakeholders. |
| ***Oceania*** | |
| Marshall Islands | There are cases where materials derived from coral reefs were planned to be used. In some cases, coral reef-derived aggregate was avoided, and the project was planned to import materials from third countries. |
| Solomon Islands | There is a case where sourcing aggregates became difficult due to environmental considerations. No cases were identified involving the use of materials derived from coral reefs. |
| Palau | There are cases where materials derived from coral reefs were used as construction materials, as well as cases where the foundation soil was derived from coral. |

*Source: JICA Study Team*

Information on problem soil in road and transport for the projects from other financers was gathered. The summary is as follows:

Table 3.1.2 Summary of projects from other donors

| Country/ Donor | Project Name/ Year of Project Start | Soil-related Information | Local Implementing Agencies |
|---|---|---|---|
| Ethiopia/ World Bank (WB) | Ethiopia-Road Sector Development Program APL4/ 2009 | Distribution of residual soils, alluvial soils, and Vertisols prone to soil erosion along the road alignment. | Ethiopia Roads Authority (ERA) |
| Ethiopia/ WB | Road Sector Support Project/ 2014 | Distribution of residual soils and alluvial soils prone to soil erosion along the road alignment. | ERA |
| Ethiopia/ WB | Ethiopia-Transport Sector Project in Support of RSDP4/ 2012 | Distribution of Black Cotton Soil and residual soils. | ERA |
| Ethiopia/ WB | ET-Road Sector Dev. Stage Ⅲ Proj. (APL3) in support of Govt's RSDP/ 2007 | Distribution of Black Cotton Soil around river crossings, soils prone to erosion along the target road. | ERA |
| Ethiopia/ WB | ET-Road Sector Proj (APL2) to support Govt's RSDP/ 2005 | Distribution of Red Soil. | Not provided |
| Ethiopia/ WB | Tanzania Transport Integration Project/ 2022 | Black Cotton Soil mainly distributed near rivers. Marine Clay is also partially distributed. | Tanzania National Roads Agency (TANROADS) |
| Ethiopia/ WB | Tanzania Roads to Inclusion and Socioeconomic Opportunities (RISE)/ 2021 | Partial distribution of Black Cotton Soil. | TANROADS; Tanzania Rural and Urban Roads Agency (TARURA) |
| Ethiopia/ WB | Dar es Salaam Urban Transport Improvement Project/ 2017 | Areas where the lower soil is predominantly Marine Limestone. | TANROADS; Dar Rapid Transit Agency (DART) |
| Ethiopia/ WB | Dar es Salaam Metropolitan Development Project/ 2015 | Existence of coral reef-derived limestone near the coast. | Not provided |
| Ethiopia/ | Second Central Transport | Distribution of calcareous soils | TANROADS; |

| Country/ Donor | Project Name/ Year of Project Start | Soil-related Information | Local Implementing Agencies |
|---|---|---|---|
| WB | Corridor Project/ 2008 | along coast and residual soils. | DART |
| Ethiopia/ WB | Central Transport Corridor Project/ 2004 | No environmental report available. | Not provided |
| Ethiopia/ WB | Transport Sector Support Project/ 2010 | Areas with a high silt content, where soils prone to erosion are distributed together. | TANROADS |
| Ghana/ WB | Transport Sector Improvement/ 2017 | Areas with laterite-derived soils are present. | Ministry of Roads and Highways; Ministry of Transport |
| Guinea/ WB | Rural Mobility and Connectivity/ 2019 | No environmental report available. | Not provided |
| Liberia/ WB | Southeastern Corridor Road Asset Management Project/ 2019 | No mention of problem soil. | Infrastructure Implementation Unit (IIU) of the Ministry of Public Works |
| Cambodia/ WB | Road Rehabilitation Project/ 1999 | Distribution of sulfate soils and dispersive soils was confirmed. | Not provided |
| Cambodia/ Asian Development Bank (ADB) | Transport Infrastructure Development and Maintenance/ 2018 | Distribution of laterite (Ferruginous gravels) has been confirmed. | Not provided |
| Laos/ WB | National Road 13 Improvement and Maintenance/ 2018 | Distribution of kaolinite and laterite has been confirmed. | Ministry of Public Works and Transport |
| Indonesia/ WB | Mass Transit Project/ 2022 | Distribution of latosol has been confirmed. | Ministry of Transportation |
| Kyrgyzstan/ WB | First Phase of the Central Asia Road Links Program/ 2014 | Distribution of loess (yellow earth) has been confirmed within the country. | Ministry of Transport and Roads |
| Tajikistan/ ADB | Road Network Sustainability Project/ 2020 | Confirmation of soils prone to erosion. | Ministry of Transport |
| Marshall Islands/ WB | Sustainable Energy Development Project/ 2017 | The entire island is composed of a coral atoll. | Marshalls Energy Company |
| Solomon Islands/ ADB | Land and Maritime Connectivity Project/ 2021 | Distribution of organic soils and others. | Ministry of Finance and Treasury |

*Source: JICA Study Team*

## 3.2 Issues of ODA Projects Related to Problem Soil

Based on the results of interviews, field surveys, and other information gathered, the following summary has been compiled.

Table 3.2.1 Issues in projects encountering problem soil

| Stage | Issues | Case |
|---|---|---|
| Feasibility Study Stage (FS) | Understanding of soil distribution | Problem soils are widely distributed in some countries due to the lack of soil distribution maps. Extensive preliminary soil surveys are required during the FS stage. |
| | Selection of testing methods | There are no established standards for problem soil testing, making it difficult to select appropriate testing methods. |
| | Selection of materials | Securing suitable borrow pits is difficult. Budget constraints may require using nearby materials, potentially causing issues. |

| Stage | Issues | Case |
|---|---|---|
| Bacis Design Stage (BD)/ Detailed Design Stage (DD) | Selection of countermeasures | Appropriate countermeasures should be selected based on the type of problem soil. For example, for expansive soils, options like soil replacement or improvement should be considered, taking into account local conditions and cost-effectiveness. |
| | Standards for soil testing | Sampling expansive soils can be challenging due to difficulties in determining the appropriate number of samples and dealing with soil variability. |
| | Application of design standards | In countries like Palau, where no national building design standards are in place, using international standards can lead to higher construction costs. |
| | Appropriate drainage planning | Heavy rain and flooding increase the risk of slope erosion and landslides, making proper drainage and maintenance planning essential. |
| | Design changes considering soil conditions | In Kyrgyzstan, large cobbles were encountered in the stratigraphy during bridge foundation work, making it impossible to install sheet piles. This highlights the need to anticipate actual soil conditions and revise the design accordingly during the planning stage. |
| | Ensuring constructability | When using laterite as embankment material, workability significantly decreases during rainy conditions, so careful control of moisture content is essential. |
| | Vegetation control measures | Since laterite is not conducive to vegetation growth, measures such as mortar protection or special techniques to promote vegetation may be necessary to prevent slope erosion. |
| | Consideration of inspection methods | On Cambodia's National Route 8, dragon holes caused by dispersive soils led to the removal of pavement and rebuilding of the subgrade. Problem areas are identified through visual inspections during regular maintenance. |
| | Inspection accuracy | In Thailand, road inspection techniques are used to assess the ground conditions, but the accuracy is lower than that of borehole surveys. |
| | Consideration of maintenance and management | In Cambodia, dragon holes occur every time it rains, requiring annual repairs, which can result in high maintenance costs and effort. |
| Construction Stage (CS) | Impact of weather conditions | The area is described as prone to flooding, which could lead to soil liquefaction and softening. |
| | Insufficient reflection of soil survey results | The results of the soil investigation at the design stage were not adequately reflected in the construction plan, which may lead to construction-related issues. |
| | Unclear measures for problem soils | Specific construction procedures for proble soil are not detailed in the construction plan. There may be concerns regarding quality assurance. |
| | Inadequate quality control plan | Management plan for ensuring the quality of problem soil measures (such as testing methods, frequency, and standard values) is not specifically defined. This could lead to difficulties in ensuring quality. |
| | Lack of cases and measures sharing | Past problem soil cases, including causes and preventive measures, should be shared within construction plan. |
| Other | Need for technical support | Japan's technical support is needed for soil testing, countermeasures, and ground improvement. |
| | Capacity building | Although testing equipment was granted from Japan, there is a shortage of skilled personnel, capacity building is also an important issue. |

*Source: JICA Study Team*

# CHAPTER 4. JAPAN'S MEASURES FOR PROBLEM SOIL, GROUND REINFORCEMENT TECHNIQUE AND SLOPE TREATMENT TECHNIQUE

In this chapter, the applicability of Japanese technology for problem soils in overseas ODA projects is examined. Basic information on ground improvement and embankment treatment technologies in Japan, including the history, development, methods, basic principles of planning, investigation, and design is compiled.

## 4.1 JAPAN'S MEASURES FOR PROBLEM SOIL AND REINFORCEMENT TECHNIQUE

### 4.1.1 History of Problem Soil and Reinforcement Measures

#### 4.1.1.1 Ground Improvement Technology

In Japan, ground improvement technology developed to address problem soils such as alluvial soils, soft ground, organic soils, peat, and scoria, which are commonly found in the country. Japan, with its limited land area and high population density, faces the challenge of conducting various development and construction activities even on problematic ground, leading to demanding situations in the progress of these projects. Therefore, Japan has long developed technologies for addressing soft ground issues, and it has become a leader in soft ground improvement techniques, with various ground improvement methods widely adopted globally.

#### 4.1.1.2 Effective Utilization of Excavated Soil

In Japan, soil and sludge generated as by-products of construction projects (referred to as excavated soil) often face issues such as a shortage of suitable disposal sites, illegal dumping, and complaints from residents. The widespread recognition of the environmental burden caused by the increasing amount of excavated soil, may hinder future development. To make the most of the local materials as far as possible, efforts have been made to utilize various types of problem soils and unsuitable materials for construction such as soil improvement methods.

### 4.1.2 Current Status and Development Trends of Japanese Technology Expected to Be Applied in Overseas ODA Projects

#### 4.1.2.1 Basic Principles of Ground Improvement Technology

In Japan, ground improvement technologies are classified and organized based on basic principles, as outlined in works such as “Ground Improvement Investigation, Design, and Construction – From Single-family Homes to Artificial Islands (March 2013)” and “Road Construction – Soft Ground Measures Guideline.” Ground improvement has a wide range of techniques. To select the appropriate method from the various available options, it is necessary to understand the characteristics of them as preliminary knowledge.

The basic principles of ground improvement can be broadly classified into: (1) Replacement; (2) Consolidation/Drainage; (3) Compaction; (4) Chemical Treatment and (5) Reinforcement.

Table 4.1.1 provides an overview of each basic principle. Individual methods may not always be based on a single principle; often, multiple principles are combined. Additionally, the approach may vary depending on the type of ground, the application method, and the designer's perspective. The methods shown in Table 4.1.1 are not always selected in isolation, and in some cases, a combination of methods may be more effective depending on the conditions.

Table 4.1.1 Basic principles of ground improvement technology

| Basic Principle | Method Name | Description |
|---|---|---|
| Replacement | Replacement Method, etc. | Remove soft soil or problem soils that are expected to cause major issues during construction, and replace them with high-quality materials of different properties. |
| Consolidation and Drainage | Embankment Loading Method, Surface Drainage/Sand Mat Method, Slow Loading Method, Vertical Drain Method, Vacuum Consolidation Method, etc. | Increase soil strength or reduce post-construction settlement by promoting drainage or consolidation of the ground. |
| Compaction | Vibratory Rod Compaction Method, Static Compaction Method, etc. | Compact the soil by inserting sand or applying dynamic loads to increase strength, prevent liquefaction, and reduce settlement. |
| Chemical | Cementation Method, Freezing Method, etc. | Mix additives such as cement with soil to solidify the ground through chemical reactions, or use heat treatment (freezing) to alter the soil properties. |
| Reinforcement | Backfilling Method, Sheet Pile Method, Lightweight Embankment Method | Introduce different materials from the original ground to share significant forces (compression, tension, shear), and reduce stress, settlement, and sliding forces by constructing embankments with lightweight materials. |

*Source: JICA Study Team*

#### 4.1.2.2 Current Status of Effective Use of Excavated Soil

Standards for appropriate utilization of excavated soil have been provided by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) in the “Standards for the Use of Excavated Soil” (August 10, 2006). Technical guidelines for using excavated soil as construction material are summarized in the Technical Manual for the Use of Excavated Soil in Construction Projects. These standards define soil classification criteria to select appropriate uses for excavated soil. Even low-quality soil can be rendered usable through suitable improvement techniques, depending on the intended application. The manual outlines such applicable improvement methods and construction techniques.

The usage of excavated soil is guided by "Application Suitability Standards," which correspond to soil classification. These standards emphasize compliance with public specifications and allow low-quality soil to be used if proper soil improvement is applied. They serve as general guidelines and must be interpreted with flexibility, based on the type and importance of the structure. The evaluation criteria are as follows:

◎: Usable as-is

○: Usable after proper soil improvement (e.g., reducing water content, adjusting gradation, functional additives or reinforcement, stabilization treatment)

△: Requires more time and cost for improvement compared to ○

×: Not usable even after soil improvement, unless mixed with good quality material

Soil improvement methods applicable for the use of excavated soil can be broadly classified based on their application stage and location, as shown in Table 4.1.2.

(1) Pre-excavation methods refer to improvement techniques applied to the soil before excavation.

(2) Post-excavation methods are applied after excavation and can be implemented at the excavation site, intermediate treatment facilities, or the final use site.

(3) On-site methods are applied directly at the location where the soil is used.

Table 4.1.2 Classification of major soil improvement methods

| Method Category | (1) Pre-excavation Method | (2) Post-excavation Method | (3) On-site Method |
|---|---|---|---|
| Moisture Content Reduction | - Excavation with groundwater lowering<br>- Drainage | - Air drying<br>- Forced dewatering<br>- Mixing with good quality soil<br>- Dewatering in bags | - Dewatering in bags |
| Grain Size Adjustment | - | - Sieving<br>- Mixing with good quality soil<br>- Selective transport | - |
| Function Enhancement / Reinforcement | - | - | - Dewatering in bags<br>- Sandwich method<br>- Flowable soil method<br>- Foam-mixed soil method<br>- Lightweight soil mixing<br>- Fiber-reinforced soil<br>- Reinforced soil method |
| Stabilization Treatment | - Mixing stabilizers before excavation | - Stabilization treatment<br>- Flowable soil method<br>- Foam-mixed soil method<br>- Various ground improvement methods | - Pre-mixed stabilization<br>- In-situ stabilization treatment |

*Source: JICA Study Team*

#### 4.1.2.3 Overseas Deployment Cases

This section investigates overseas deployment cases of ground improvement and excavated soil treatment technologies developed in Japan.

**(1) Survey of Associations**

Questionnaire surveys were conducted for the following associations:

- Cement Association
- High-Grade Soil Research Consortium
- CDM Research Committee
- Permeation Solidification Method Research Group
- Japan Fly Ash Association
- DJM Method Association
- Vacuum Consolidation Technology Association
- Power Blender Method Association

Table 4.1.3 List of survey items

| No. | Items |
|---|---|
| 1 | Company name |
| 2 | Existence of overseas deployment cases of ground improvement technology |
| 3 | Countries where the technology was deployed |
| 4 | Period of overseas deployment |
| 5 | Name of the ground improvement method applied overseas |
| 6 | Unit price of the applied ground improvement technology in Japan (materials and construction) |
| 7 | Geological and soil information related to the ground improvement project |
| 8 | Difficulties, issues, and challenges faced during the deployment of the technology, how they were addressed, and the current status |
| 9 | Future plans for overseas deployment and current constraints or challenges in expanding overseas |

*Source: JICA Study Team*

**(2) Literature Review**

A literature review was conducted by selecting several companies involved in overseas deployment under JICA's Project Formulation and Dissemination Projects. Additional literature and information were also reviewed as provided by members of the expert committee. While each company is actively working toward wider adoption, it was found that challenges extend beyond technology itself—such as "completion of cost estimation data and improvement of construction ordering systems" and "verifying applicability through field trials and accumulating performance records."

**(3) Interviews**

Interviews were conducted with companies experienced in overseas deployment of ground improvement technologies:

- Case study of deep mixing method applied to expansive clay soil overseas (Fudo Tetra Corporation)
- Case study of soil improvement using excavated soil (JDC Corporation)

### 4.1.3 Investigation and Design Methods

#### 4.1.3.1 Investigations Related to Ground Improvement

This section provides an overview of general investigation and design methods for soft ground countermeasures, mainly referring to "Road Earthworks: Guidelines for Soft Ground Countermeasures (2012 Edition)".

**(1) General Investigations**

In road construction projects, investigations for soft ground are generally divided into five stages: (1) preliminary investigation and study during the planning stage, (2) basic investigation and study during the basic design stage, (3) detailed investigation, additional investigation, and trial construction during the detailed design stage, (4) investigation during construction, and (5) investigation during the maintenance stage; particular care is required when the ground conditions involve a sloping foundation of soft layers, marine clay, peat, or a combination of peat and marine clay.

#### (2) Investigation of Problem Soil

In investigations of problem soils, the basic approach is to understand the distribution of terrain and geology through methods such as boring and trial excavation, and to conduct soil tests on collected samples as in domestic investigations; however, in addition to test methods, the procedures for sampling, including frequency and sampling depth, are also major challenges in the investigation of problem soils. Examples of test methods used to identify problem soils—mainly expansive and dispersive soils—are mostly standardized by ASTM International, the world's largest private, non-profit international standards organization, while in India, where black cotton soil is widely distributed, certain tests such as the free swell index test are standardized independently by Indian Standards (IS).

#### (3) Trends in Road Inspection Technologies

In the maintenance and management of roads after opening to traffic, problem soils may cause surface deformation, cracking, or subsidence; in such cases, if these soils were not identified during the initial investigation, it is important to conduct timely inspections and utilize inspection technologies to identify the influencing factors before significant damage occurs. Several examples of current Japanese road inspection technologies are summarized.

### 4.1.3.2 Design and Construction Related to Ground Improvement

#### (1) Overview

When designing soil-structure works and measures for soft ground, it is necessary to consider the compatibility with intended use, structural safety, durability, construction quality, ease of maintenance, environmental harmony, and cost-effectiveness. As a principle, performance requirements for the soil-structure works are set based on anticipated actions.Methods for verifying these requirements are examined, such as logically valid methods or experimental verification. Approaches based on past experience or recognized methods are also adopted where applicable.

#### (2) General Design of Soft Ground Improvement Measures

#### 1) Consideration and Selection of Improvement Measures

When selecting soft ground improvement measures, it is important to fully understand the problems encountered in soil-structure works, such as settlement, stability, and deformation of surrounding soil. There are various improvement methods, each with its characteristics and different effects. Therefore, the reason and purpose for applying improvement measures must be fully understood, along with an accurate assessment of the nature of the soft ground and considering structural and construction conditions. The principles, effects, construction methods, impacts on surrounding areas, and cost-effectiveness of the improvement measures must be comprehensively reviewed to select the most suitable and proven methods. Improvement methods may be applied individually or in combination depending on the situation, so the optimal method should be selected from various perspectives.

#### 2) Design of Improvement Measures

In the design of soft ground improvement measures, results from ground surveys should be fully utilized to check the stability of soil-structure works built on improved soft ground and to determine the most suitable improvement methods to achieve the intended goals. Various methods exist for soft ground improvement, and they should be selected based on logical validity, experimental verification, and accumulated experience and practices.

#### 4.1.3.3 Investigation Related to the Use of Excavated Soil

For soil classification, the standard method is to perform cone index testing and physical tests on compacted soil. In the case of improved soil, only the cone index is measured. If the intended use is limited, separate standards may apply based on the intended use of the soil. In addition to soil sample observation, tests on grain size composition are required to classify soil materials using engineering classification systems. Liquid limit, plastic limit, and natural moisture content tests are essential for understanding the fundamental properties of the soil, especially for fine-grained soils. For problem soils, it is important to conduct sufficient tests to understand the properties of each type of problem soil, but further research and practical experience are necessary for accumulation of knowledge.

#### 4.1.3.4 Design and Construction Related to the Use of Excavated Soil

The use of excavated soil is generally based on applied usage standards, and the design must follow the standards for the relevant structure. During construction, it is crucial to accurately understand the required quality for the intended use of the excavated soil and establish appropriate construction management based on this understanding. The party generating the soil should provide detailed data on soil classification, soil properties, volume, and timing of excavation to the user and ensure the soil fulfills the desired quality for its intended use. Proper construction management is essential to prevent any degradation of soil quality during excavation or temporary storage. The user should conduct soil testing at intervals agreed upon during consultations with the generator and verify that the quality meets the required specifications for the intended use, potentially conducting trial constructions where necessary.

### 4.1.4 Construction Management / Supervision Methods

To meet the objectives of soft ground improvement, proper design as well as construction and construction management are critical. The construction of soft ground improvement works must meet specified quality, shape, and dimensions of the structures within the prescribed time frame and cost-effectively. Therefore, understanding the characteristics of the chosen improvement method, developing a construction plan suitable for local conditions, and conducting trial constructions when necessary to verify processes, quality, and outcomes are essential. Furthermore, to address issues like settlement, stability, and deformation of surrounding soil, it is important to confirm that intended effects of the improvement measures have been achieved, and to implement dynamic observation and information-based construction methods to handle unforeseen situations caused by soil heterogeneity or uncertainty in predictions. Construction management related to settlement and stability must also be conducted accordingly.

## 4.2 SLOPE TREATMENT TECHNOLOGY IN JAPAN

This section investigates and compiles information on the history, current status, overseas deployment cases, research/design methods, and construction management/supervision methods related to slope treatment technology in Japan. The focus of this study is primarily on "road embankments," with "cutting" and "slope disaster prevention" being excluded as they are not the main subjects of this investigation.

### 4.2.1 Definition and History of Slope Treatment Technology

According to the "Road Earthworks Cutting and Slope Stability Guidelines (FY 2009 edition)," slope treatment technology is defined as shown in Figure 4.2.1. Slope treatment applies to both cutting and embankment works, encompassing "slope works" and "slope protection works."

"Slope protection works" involve covering the slope with vegetation or structures to ensure slope stability, preserve the natural environment, and enhance the landscape. These works are classified into "slope greening works" and "structural works."

"Slope greening works" involve establishing vegetation on the slope to prevent weathering and erosion, while also contributing to environmental preservation and landscaping. Since vegetation is involved, it is important to note that the effects take time to manifest, and these works are susceptible to influences such as rainfall and temperature fluctuations after construction.

"Structural works" are applied to ensure the long-term stability of the slope by preventing erosion, weathering, surface sliding, and collapse. These works are used in cases where: 1) "slope greening works" are not suitable for the slope, 2) "slope greening works" alone cannot ensure long-term stability against erosion, or 3) there is a risk of surface collapse, landslides, or falling rocks, resulting in potential instability.

- Slope Work / Slope Stabilization Work
  - Slope Work
    - Excavation Work
    - Slope Protection Work
      - Slope Greening Work
      - Structural Work
  - Slope Stabilization Work
    - Slope Failure Countermeasures
    - Rockfall Countermeasures
    - Rock Slope Failure Countermeasures
    - Landslide Countermeasures
    - Debris Flow Countermeasures

*Source: Road Earthworks: Cut Earthworks and Slope Stability Works Guidelines, Japan Road Association, p.11, 2009.*

Figure 4.2.1 Classification of slope works and slope stability works

Slope greening work is a technique developed after World War II. Before that, civil engineering projects involved manual cut-and-fill work, which limited the area of slopes that could appear at one time. After the war, heavy machinery such as bulldozers were introduced, allowing large-scale construction to be completed in a short period of time. As a result, the area of slopes appearing at one time increased, and there was a demand for rapid erosion control on embankment slopes. This led to the development of mechanized construction techniques. Consequently, plants suitable for mechanized construction were required, and the method of planting stumps and seedlings, used in traditional mountain greening, shifted to sowing pasture seeds. Structural works, on the other hand, have traditionally used natural materials such as stones and gravel for civil engineering structures like embankments and revetments, as well as for buildings like castles. In the 20th century, with the spread of concrete products, structural works using concrete were developed.

### 4.2.2 Current Status and Development Trends of Japanese Slope Treatment Techniques Expected to be Applied in Overseas ODA Projects

#### 4.2.2.1 Current Status of Japanese Slope Treatment Techniques

This section summarizes the specific types and overviews of slope protection works conducted in Japan. The classification and summary of slope protection works were compiled with reference to the "Road Earthworks: Cut Earthworks and Slope Stability Works Guidelines (2009)" and "Construction Materials Prices."

Slope greening work is mainly classified into three types: (1) seeding work, (2) planting work and (3) seedling installation spraying work. On the other hand, "structural works" are broadly categorized into 19 methods, providing a wide range of options based on their application. Among the 19 methods, 7 methods are applicable as "greening foundation works" and are used in combination with slope greening work.

Table 4.2.1 Types of slope protection works

| Slope Greening Work | Structural Work |
|---|---|
| (1) Seeding Work<br>(2) Planting Work<br>(3) Seedling Installation Spraying Work | (1) Wire Mesh Installation (Greening Foundation Work)<br>(2) Fiber Net Installation (Greening Foundation Work)<br>(3) Fence Work (Greening Foundation Work)<br>(4) Gabion Work<br>(5) Precast Frame Work (Greening Foundation Work)<br>(6) Mortar/Concrete Spraying Work<br>(7) Stone Cladding Work<br>(8) Block Cladding Work<br>(9) Concrete Cladding Work<br>(10) Sprayed Frame Work (Greening Foundation Work)<br>(11) Cast-in-place Concrete Frame Work (Greening Foundation Work)<br>(12) Stone Masonry, Block Masonry Retaining Wall Work<br>(13) Basket Work<br>(14) Timber Beam Retaining Wall Work<br>(15) Concrete Retaining Wall Work<br>(16) Continuous Long Fiber Reinforced Soil Work (Greening Foundation Work)<br>(17) Ground Reinforcement Soil Work<br>(18) Ground Anchor Work<br>(19) Pile Work |

*Source: JICA Study Team*

#### 4.2.2.2 Overseas Deployment Cases of Japan's Slope Protection Technology

This section investigates the overseas expansion cases of slope protection technologies developed in Japan.

**(1) Survey of Associations**

The association surveys were conducted through questionnaires sent to the following organizations. The contents of the surveys are shown in Table 4.2.2.

- NPO Japan Greening Association
- General Incorporated Association National Slope Protection Association

Table 4.2.2 List of survey items

| No. | Item |
|---|---|
| 1 | Company name |
| 2 | Existence of overseas deployment cases of slope protection technology |
| 3 | Countries where the technology was deployed |
| 4 | Period of overseas deployment |
| 5 | Name of slope protection technology applied overseas |
| 6 | Unit price of the applied slope protection technology in Japan (materials and construction) |
| 7 | Type of slope applied overseas (embankment slope or excavation slope) |
| 8 | Geological and soil information of the slope |
| 9 | Difficulties, issues, and challenges faced during the deployment of the technology, how they were addressed, and the current status |
| 10 | Future plans for overseas deployment and current constraints or challenges in expanding overseas |

*Source: JICA Study Team*

#### (2) Literature Review

The literature review was conducted by picking up several companies involved in overseas deployment through JICA project investigation and promotion activities. It was confirmed that all of the companies are working hard to promote their technology. However, it was also found that in addition to technological challenges, non-technical issues such as "incorporation into local technical standards," "acquisition and selection of local agents, import procedures," and "applicability in the local area (demonstration experiments)" exist.

### 4.2.3 Survey and Design Methods

This section summarizes the general survey and design methods for road embankments (mainly from the materials perspective) and slope protection works, based on "Road Engineering Embankment Guidelines (2010 Edition)" and "Cutting Works and Slope Stability Guidelines (2009 Edition)."

### 4.2.3.1 Road Embankment Survey

#### (1) General Survey

Road embankment surveys are divided into five major stages: (1) preliminary survey stage (planning), (2) preliminary survey stage (preliminary design), (3) detailed survey stage (detailed design), (4) construction stage, and (5) maintenance stage. When conducting surveys for embankment materials, the following items should be noted, with particular attention to various characteristics as shown in the table below.

Table 4.2.3 Embankment materials requiring special attention

| Item | Content |
|---|---|
| Soils with Stability Issues in Embankments | The shear strength of cohesive soils is relatively weak, so when constructing embankments primarily composed of cohesive soils, stability checks for the embankment are necessary.<br>→ Conduct triaxial compression tests considering strength reduction due to remolding. |
| Soils with Trafficability Issues | When using high moisture content clay, sandy silt, etc., it is necessary to consider trafficability.<br>→ Select appropriate machinery, understand strength reduction characteristics due to remolding (conduct cone index tests), and improve trafficability by mixing with good quality materials. |
| Soils Prone to Erosion from Rain | Sandy materials like loess, mountain sand, and shirasu are prone to erosion and collapse of the embankment due to rainfall during construction or afterwards.<br>→ Focus on natural moisture content and optimal moisture content, and confirm the relationship between moisture content changes and strength changes. |
| Soils Prone to Weathering (Fragile Rocks) | Mudstone, shale, tuff, weathered serpentine, crushed rock, weathered schist, and altered andesite from the Neogene period are weak rocks prone to slaking and crushing.<br>→ Conduct slaking tests and crushing tests on the rocks to evaluate their slaking properties. For slaking materials, construction methods that minimize voids during excavation, such as using smaller particle sizes and crushing and compacting after thin-layer spreading, should be considered. |
| Soils Difficult to Spread (Rock Fragments, Gravel, Pebbles) | Hard rock materials are difficult to crush and have larger particle sizes compared to general soil.<br>→ Conduct preliminary surveys to determine the maximum particle size and particle size distribution. Additionally, when different materials are placed over rock-filled embankments, rainfall may cause the material to sink into the gaps between rocks, resulting in uneven settlement. In such cases, introducing a particle size-adjusting intermediate layer is effective. |

| Item | Content |
|---|---|
| Soils Prone to Frost Heave Damage | In cold regions, there is a possibility of frost heave damage.<br>→ Perform tests to determine frost susceptibility and implement countermeasures such as replacement methods. |

*Source: JICA Study Team*

**(2) Slope Protection Works Investigation**

**1) Vegetation Works Investigation**

To meet the prerequisites for establishing vegetation on embankments using vegetation works, the following investigations are conducted:

- Investigation of Surrounding Environment
- Meteorological Survey
- Investigation of Surface Soil and Existing Trees
- Market Survey of Plant Materials
- Investigation of the Embankment at the Time of Construction

Since vegetation works involve using plants as materials, the location conditions of the construction site significantly affect the outcome.

#### 4.2.3.2 Road Embankment Design

**(1) General Design**

When designing road embankments, it is necessary to ensure consistency with the intended use, safety of the structure, durability, quality control during construction, ease of maintenance, harmony with the environment, economic feasibility, and performance requirements for anticipated actions. If existing specifications (such as materials and construction methods) are considered capable of meeting these performance requirements based on past experiences and achievements, they can be utilized within the appropriate scope of application.

**(2) Slope Protection Works Design**

For designing slope protection works, it is important to select appropriate methods based on local conditions such as topography, geology, materials, and landscape. When selecting the method, considerations such as ensuring stable slopes, the need for vegetation, material usage, and erosion resistance should be considered.

**1) Design of Vegetation Works**

- The design of vegetation works is regulated by the following three aspects:
- Select plant materials and construction methods that are appropriate for the location conditions etc. that will enable the formation of the target plant communities for greening.
- Materials to be used for vegetation work will be selected that are appropriate for the characteristics of the area to be greened, such as invasive species and native species, and materials to form the growth base will be appropriate for the type of work and plants to be used.
- Vegetation work will be designed with consideration for the maintenance and management of the slope.

In selecting methods, it is important to consider characteristics of plant materials, local climate, embankment soil, slope gradient, and the construction period. Additionally, the necessity of green infrastructure should be assessed.

**2) Design of Structural Works**

For structural works, the long-term stability of the embankment is a key consideration. Using empirical methods or appropriate load settings, the required materials, shapes, and dimensions should be considered. The design should also reflect the results of investigations such as the anticipated scale of occurrences, environmental impacts, and erosion or surface collapse prevention. When aiming to prevent or reduce phenomena such as weathering, erosion, or rock-layer peeling, empirical methods are often used to determine the materials, shapes, and required qualities. Since surface water or groundwater often causes embankment collapse, when there is groundwater or surface water flowing onto the embankment, combined drainage works are necessary.

### 4.2.4 Construction Management/Supervision Methods

This section outlines general construction management and supervision methods for road embankments and slope protection works based on the "Road Earthworks Embankment Works Guidelines (2010 Edition)" and "Cutting Earthworks & Slope Stability Works Guidelines (2009 Edition)."

**(1) General Construction Management/Supervision**

During construction, it is essential to adhere to the conditions set to ensure that the embankment meets the performance requirements specified in the design. However, unforeseen circumstances such as encountering unexpected materials or conditions (e.g., soil behavior, weather conditions) may arise, and flexibility is required to adapt appropriately. The materials used for embankments should be easy to handle, maintain the stability of the embankment, and avoid harmful deformations. Local soil should be utilized wherever possible, and if the soil is unsuitable, proper treatment such as ground improvement should be conducted. The construction should adapt to local terrain and geology while maintaining the shape and quality specified in the design documents. Natural phenomena such as weather and environmental considerations should be factored into the construction process. Economic feasibility, speed, certainty, and safety are critical factors, therefore thorough construction planning in advance is essential.

Environmental Impacts: Construction activities can generate noise, vibration, soil runoff causing water pollution, dust from soil transportation, and subsidence from embankment works. These impacts can affect the surrounding environment and smooth project execution. Thus, careful attention should be paid when selecting methods, construction machinery, and work procedures during planning and implementation.

**(2) Slope Protection Works Construction Management/Supervision**

**1) Vegetation Works Construction**

When constructing vegetation works, it is important to consider factors like construction timing, project management, quality control, and safety. Additionally, attention should be paid to conditions such as groundwater, weather, material quality, and seedling measurements.

- Construction Planning: The construction should be scheduled according to the planting season for the vegetation used.
- Project Management: Ensure that seeding occurs at the appropriate time. Avoid working

immediately before or during heavy rain.

- Quality Control: Use consistent quality materials. Moreover, ensure accurate measurement of seeds during seeding work. The correct application thickness should be maintained, and coverage should be even to ensure reliable germination and initial growth.
- Safety Management: Ensure the safety of workers, especially those working at height or on the embankment.
- Key Considerations: Confirm that no surface water or groundwater affects the embankment before construction. Avoid construction during severe weather such as strong winds or extreme heat. Verify the quality of plant materials upon arrival and strictly measure the required amounts of seeds for each type.

**2) Structural Works Construction**

During structural works construction, it is important to account for newly discovered conditions and ensure that the work meets the functional requirement. Since conditions on the embankment may change over time or the embankment may not be present during design, it is necessary to conduct investigations regarding the geological and groundwater conditions before or during construction. Based on these results, measures should be taken to ensure the embankment meets the required functionality. During construction, it is necessary to verify that the constructed structure fulfills the functional requirement using appropriate evaluation criteria and methods. Methods include field tests, laboratory tests, or confirming results from manufacturers' certifications.

# CHAPTER 5. FIELD SURVEY (OVERSEAS SURVEY)

## 5.1 OVERVIEW OF OVERSEAS FIELD SURVEY

Based on literature review and surveys with companies and experts who have encountered problem soils in past construction projects, 13 countries were selected for field research in this study shown in Table 5.1.1. The following points were taken into consideration when selecting the countries.

- Covering all the problem soils to be studied
- Countries where problem soils were encountered in the past in ODA projects, etc.
- Consider the possibility of future ODA projects
- Whether there are research institutions that are considered to have knowledge of problem soils
- Countries where there is a high possibility of obtaining information on problem soil through on-site interviews

Table 5.1.1 Target countries for overseas field survey

| Region | Target Country | Main Target Problem Soil |
|---|---|---|
| Southeast Asia | Cambodia | Dispersive soil, Expansive soil |
| | Indonesia | Expansive soil, Peat |
| | Thailand | Expansive soil, Collapsible soil |
| Central Asia | Kyrgyzstan | Expansive soil, Loess, Erodible soil |
| | Tajikistan | Saline soil, Loess, Erodible soil |
| Oceania | Palau | Coral derived soil |
| | Marshall Islands | Coral derived soil |
| East Africa | Ethiopia | Expansive soil (Black cotton soil) |
| | Kenya | Expansive soil (Black cotton soil) |
| | Tanzania | Expansive soil (Black cotton soil) |
| West Africa | Guinea | Laterite, Expansive soil (Black cotton soil) |
| | Côte d'Ivoire | Laterite |
| | Ghana | Laterite |

*Source: JICA Study Team*

During the field survey, the Team visited relevant organizations (government entities, research institutions, engineering/construction/survey companies) which were presumed to have involved in construction projects dealing with problem soils. The contents of the questionnaire were mainly:

- Types of problem soil encountered within the country
- Standards, guidelines and manuals referring to problem soil
- Distribution maps of problem soil
- Examples encountered on problem soil
- Problem Soil Measures
- Expected Technological Demands from Japan

## 5.2 SUMMARY OF FIELD SURVEY

The summary of each country's field survey is shown in Table 5.2.1 to Table 5.2.5.

Table 5.2.1 Summary of survey by country (Southeast Asia)

| Survey Item | Description |
|---|---|
| | ***Cambodia*** |
| Problem Soil | Expansive soil, Dispersive soil, Laterite |
| Standards/Manual | ○National standards on problem soil are not established.<br>○Tests to determine dispersive soil is based on Australian standards, ASTM and other U.S. standards. International standards are used for construction. |
| Distribution Map | The government is aware of the distribution of dispersive soil and expansive soil, but the investigation method or map data is not established. |
| Examples Encountered on Problem Soil | <u>Dispersive soil</u><br>○National Route 1, 8, 11: Erosion at road shoulders and along slopes<br>○National Route 6, 7: Dragon holes appear even if the road is compacted well<br><u>Expansive soil</u><br>○Road construction at Battambang |
| Problem Soil Measures | ○Geotextile sheets used as lateral reinforcement material for repair work<br>○Expansive clays are determined when liquid limit exceeds 50%<br>○Laterite with plasticity index less than 20 are used in construction. Good quality laterite containing gravel and less clay are running out. |
| Expected Technological Demands from Japan | ○Technology of soft soil treatment, ground improvement, slope protection<br>○Construction countermeasures for revetment<br>○Establishing geological profile, geological mapping, problematic soil distribution map and Cambodian testing standard |
| | ***Indonesia*** |
| Problem Soil | Expansive soil, Clay shale, Peat, Dispersive soil, Soft soil, Coral landslide, Volcanic soil |
| Standards/Manual | ○SNI 8460:2017 (National standard regulates geotechnical design requirements)<br>○Guidelines for handling Expansive soil for road construction<br>○Guidelines for Road Embankments on Soft Soils |
| Distribution Map | Soft Soil and Peat Susceptibility Map of Indonesia and Clay Shale Distribution Map of Indonesia from the Geological Agency - Ministry of Energy and Mineral Resources published in 2019.<br>1) Soft Soil and Peat Susceptibility Map of Indonesia<br>2) Clay Shale Distribution Map of Indonesia. |
| Examples Encountered on Problem Soil | ○New Capital City project contains problematic soil. It has claystone, which is hard in nature but can be weathered and become shale.<br>○Problematic soils and landslides are common in mountainous areas in Kalimantan and Sumatera. |
| Problem Soil Measures | Chemical stabilization for clay-shale expansive soil problem: Sand, Lime kiln dust, Cement, Sugarcane bagasse, Rice husk ash, Silica, Egg shell, etc. |
| Expected Technological Demands from Japan | ○Prefabricated Vertical Drain (PVD): Used to speed up consolidation<br>○Controlled Modulus Columns (CMC): Mentioned as a solution provided by Menard Technologies<br>○Deep Soil Mixing |

| Survey Item | Description |
|---|---|
| ***Thailand*** | |
| Problem Soil | Expansive soil, Dispersive soil, Collapsible soil, Laterite, Soft soil |
| Standards/Manual | ○National standards regarding problem soil are not established.<br>○For road construction, standards such as AASHTO and ASTM are used<br>○Department of Highways (DOH) and Kasetsart University has published a manual for soil engineering properties. |
| Distribution Map | ○The locations where laterite has been discovered is recorded by Department of Highways (DOH) Central Lab<br>○Researches have located problematic soils distributed locally. National soil maps are yet to be established |
| Examples Encountered on Problem Soil | Expansive soil<br>○Buildings and roads in Mae Moh power plant experienced cracks and elevation derived by heaving of expansive soil<br>Soft soil<br>○Road/bridge subsidence have occurred within/around Bangkok when soft soil layer were thicker than expected<br>Collapsible soil<br>○Land development in Rayong experienced ground collapse due to water exposure |
| Problem Soil Measures | Expansive soil<br>○Expansive soil was replaced by bottom ash emitted by the power plant<br>○Problematic soils in project sites are disposed when detected through tests |
| Expected Technological Demands from Japan | ○Technology and method on how to construct high quality road infrastructure<br>○Technology used for road inspection<br>○Research collaboration on countermeasures for problematic soils |

*Source: JICA Study Team*

Table 5.2.2 Summary of survey by country (Central Asia)

| Survey Item | Description |
|---|---|
| | ***Kyrgyz*** |
| Problem Soil | Loess, Permafrost, Dispersive soil, Expansive soil |
| Standards/Manual | ○National standards are not established<br>○Russian standards are basically applied for infrastructure projects.<br>○There are no guidelines or standards regarding problematic soils. |
| Distribution Map | ○There is geological map covering the whole country.<br>○The Geological Institute is conducting research on soil erosion throughout the country, but no distribution maps of problematic soils have been published. |
| Examples Encountered on Problem Soil | Mountain road section near Naryn Municipality<br>○Unstable Slope with holes due to underground water in areas of red sandstone layers.<br>Roads in south-west Bishkek<br>○Continued progressive pavement damage despite high frequency of repairs. There is a high probability of subsidence. |
| Problem Soil Measures | Mountain road section near Naryn Municipality<br>○Establishment of drainage facilities and it worked for stabilization<br>Roads in south-west Bishkek<br>○Installation of Drainage facilities, replacement of unsuitable soils and several times of repair works of pavements (unsettled) |
| Expected Technological Demands from Japan | ○Safety measures such as rockfall protection, slope protection, avalanche countermeasures.<br>○Geotechnical investigation technology including non-destructive testing such as electrical exploration<br>○Seismic engineering including seismic isolation technologies |
| | ***Tajikistan*** |
| Problem Soil | Loess, Dispersive soil, Expansive soil |
| Standards/Manual | ○National standards are not established<br>○Russian standards are basically applied for infrastructure projects.<br>○There are no guidelines or standards regarding problematic soils. |
| Distribution Map | ○There is geological map covering the whole country.<br>○No soil maps including problematic soils have been published. |
| Examples Encountered on Problem Soil | Dushanbe-Obigarm road<br>The road passes through sections where loess, which is prone to collapse and dispersibility, is distributed. As a result, there is a section where:<br>(A) large-scale deformation of the bridge abutment has occurred, and a section where:<br>(B) the road continues to sink and the pavement continues to deteriorate seriously despite annual repairs. |
| Problem Soil Measures | (A) Girders of the bridge was removed (but not the superstructure), and detour road without bridge structure was constructed. The road surface is still sinking.<br>(B) Repair works are carried out periodically, but no more fundamental measures have been taken. |
| Expected Technological Demands from Japan | ○Research cooperation for improving the geological investigation and establishment of distribution maps.<br>○Road development project including operational method, Railway development project. |

*Source: JICA Study Team*

Table 5.2.3 Summary of survey by country (Oceania)

| Survey Item | Description |
|---|---|
| | ***Palau*** |
| Problem Soil | Coral derived soil |
| Standards/Manual | ○There are no building codes established domestically.<br>○Standards outside Palau such as AASHTO and ASTM are used (leads to high construction cost) |
| Distribution Map | ○There are no problem soil distribution maps.<br>○Soil survey on the whole country was conducted by United States Department of Agriculture (USDA) (latest report issued: 2011)<br>○Quarries for coral dredging are planned and selected by government |
| Examples Encountered on Problem Soil | ○Most of the ground in Palau was marsh. It was necessary to replace the ground with coral material to construct roads and buildings.<br>○There were some failures of road structures in the past but cannot determine coral material was the only cause (quality of works, etc.)<br>○Major problems may have not occurred due to low traffic volume and few heavy vehicles. |
| Problem Soil Measures | ○While coral derived soils are considered good materials for landfill and roadbed, it is necessary to properly test materials to determine its engineering properties |
| Expected Technological Demands from Japan | ○Establishment of building code<br>○Material testing environment/facility in the country (tests currently conducted outside)<br>○Database of utility location (utility survey done for every construction)<br>○Expert dispatch for technology transfer and assisting government |
| | ***Marshall Islands*** |
| Problem Soil | Coral derived soil |
| Standards/Manual | ○A national building code is established (includes a section for expansive soil but not applicable for the country)<br>○Structures are designed by engineers using their own country's code. |
| Distribution Map | ○World Bank has made recommendations of coral dredging site for sustainable development<br>○Government has database of distribution of marine life including coral types |
| Examples Encountered on Problem Soil | ○Currently no accidents caused by soil material behaviors<br>○The salt-prone environment has caused corrosion of steel bars. Buildings tend to have low durability.<br>○Major problems may have not occurred due to low traffic volume and few heavy vehicles. |
| Problem Soil Measures | ○Coral materials dredged from the lagoon side are used only for non-structural facilities.<br>○Materials dredged from the outer ocean side or imported materials are used for facilities requiring high strength. |
| Expected Technological Demands from Japan | ○Material testing environment/facility in the country (tests currently conducted outside)<br>○Expert dispatch for technology transfer and assisting government<br>○Technology to improve performance of concrete structures using coral materials (cost-effective option) |

*Source: JICA Study Team*

Table 5.2.4 Summary of survey by country (East Africa)

| Survey Item | Description |
|---|---|
| ***Ethiopia*** | |
| Problem Soil | Expansive soil, Dispersive soil, Laterite, Erodible soil, Collapsible soil, Saline soil, Volcanic ash soil, Peat, etc. |
| Standards/Manual | ○Road and Bridge Design Documents in 2013, which include some contents on problematic soils. (The guidelines used for soil test are mainly AASHTO, ASTM) |
| Distribution Map | ○There is rough and largely small-scale reconnaissance survey result of Expansive Soils distribution map in 1986.<br>○Under study<br>○ERA-RRC has developed a GIS-based map of problematic soils. |
| Examples Encountered on Problem Soil | ○Expansive soils such as Black cotton soils have been encountered in many construction projects, including roads and buildings.<br>○Roads: Addis-Debrebirhan, Addis-Ambo-Wolliso roads etc.<br>○Buildings: recently abandoned G+4 condominium in Jemo-1 and a private G+3 building in Summit localities are among those severely affected |
| Problem Soil Measures | ○Black cotton soils are mainly removed and replaced with good materials that have a CBR ratio of more than 15%.<br>○There is an example that borrow materials are placed on top of the black cotton soil, which proved to be more cost-effective. |
| Expected Technological Demands from Japan | ○Mapping, Monitoring, Countermeasure on landslides<br>○Any technology that would enable the topmost part of dark silty clay soil (say up to 10-20cm) impervious through an economical treatment<br>○Technology that would enable measurement or estimate of in-situ swell pressure<br>○Cost-effective soil stabilization techniques<br>○Big Data and Centralized Analysis Center etc. |
| ***Kenya*** | |
| Problem Soil | Expansive soil, Dispersive soil, Laterite, Coral derived soil, Collapsible soil, Volcanic ash soil |
| Standards/Manual | ○Road design manual in 1987, which includes a chapter on expansive clays.<br>○Pavement design guideline for low-volume sealed roads, which includes a chapter on expansive clays and other problematic soils.<br>○The guidelines used for soil test are BS and AASHTO. |
| Distribution Map | ○Problematic soils have not been mapped for the entire country.<br>○However, the only available material is the geological map.<br>○Black cotton soils are mainly found in central Kenya and the coastal region. |
| Examples Encountered on Problem Soil | <u>Expansive soil</u><br>○Black cotton soil was encountered in many area of Mwea irrigation project.<br><u>Dispersive soil</u><br>○There was slope failure on the coast under the Mombasa Port Area Development Project due to dispersive soils. The slope was as high as 35 meters and it failed with piles. |
| Problem Soil Measures | <u>Expansive soil</u><br>○Black cotton soil was removed from the canals and replaced with laterite (murram)<br><u>Dispersive soil</u><br>○The countermeasure was to drive deeper piles |
| Expected Technological Demands from Japan | ○Geotextiles<br>○Slope protection such as drainage treatment around soils<br>○Funding training seminars on countermeasures to problematic soils such as retaining walls<br>○Countermeasures for flooding which heavily affects the country.<br>○Transfer of knowledge in geotechnical design |

| Survey Item | Description |
|---|---|
| ***Tanzania*** | |
| Problem Soil | Expansive soil, Dispersive soil, Laterite, Coral derived soil, Volcanic ash soil, Saline soil, etc. |
| Standards/Manual | ○Pavement and Materials Design Manual in 1999, which include a chapter on problematic soils.<br>○The guidelines used for soil test are Field Testing Manual in 2003 and Laboratory Testing Manual in 2000. |
| Distribution Map | ○Currently establishing materials information system which when finalized it will be useful in the various stages of road provision. |
| Examples Encountered on Problem Soil | Although countermeasures were described in guidelines and are implemented, problems still occur.<br>○Bagamoyo-Msata road in Coast Region. The road traverses a flat plain with black cotton soils of high degree of expansiveness, as high as 105.<br>○Countermeasures were applied as guided by the PMDM, but damages still occurred. |
| Problem Soil Measure | ○For dispersive soil, example for the road project called Meela bonga (funded by ADB & JICA), the countermeasure is made by concrete retaining wall and planting grass. |
| Expected Technological Demands from Japan | ○Slope instability-slope failures especially on cut sections and high fills and countermeasures<br>○Geo-engineering, including exploration techniques and analysis software<br>○Climate-resilient designs (review climate map in Tanzania)<br>○Treatment of soft grounds<br>○Improvement of marginal materials |

*Source: JICA Study Team*

Table 5.2.5 Summary of survey by country (West Africa)

| Survey Item | Description |
|---|---|
| | ***Guinea*** |
| Problem Soil | Laterite, Expansive soil, Soft soil |
| Standards/Manual | 〇General Guidelines for Roads and Railways in Guinea, don’t include a chapter for problematic soils<br>〇French standards are applied for pavement design, soil investigation, etc. |
| Distribution Map | 〇Laterite is distributed throughout Guinea. However, its properties vary from region to region.<br>〇Soil map including problematic soils has not been published |
| Examples Encountered on Problem Soil | 〇There are many sections of trunk roads with severely damaged pavements and poor runnability (e.g. National Road No.1, between Mamou and Falana). |
| Problem Soil Measures | 〇Unsuitable soil (0.5-1.0m) is removed and replaced by suitable soil material. Such as boulder, suitable laterite with high CBR<br>〇However, the measure does not always work well enough |
| Expected Technological Demands from Japan | 〇Research cooperation between industry, government and academia on the formulation of standards and guidelines and soil testing regarding problematic soils.<br>〇Enhancement of the road network database, such as linking geotechnical and soil information to it.<br>〇Earthquake Engineering including seismic resistant technologies. |
| | ***Côte d'Ivoire*** |
| Problem Soil | Laterite, Dispersive soil, Expansive soil, Soft soil |
| Standards/Manual | 〇French standards are basically applied for infrastructure projects.<br>〇There are no guidelines or standards regarding problematic soils.<br>〇Now LBTP (one of Gov. org) are preparing a document regarding countermeasures on problematic soils for publication. |
| Distribution Map | 〇There is a general soil map in the Abidjan area, but no maps of problematic soils covering the whole country.<br>〇LBTP or other organisation conducting research to produce maps |
| Examples Encountered on Problem Soil | The section near Abidjan on the Abidjan-Yamoussoukro Expressway<br>〇Deteriorated/vulnerable sections of pavement. Many cracks is observed one year after rehabilitation.<br>〇Repairs were carried out together with the installation of drainage facilities to treat high groundwater levels.<br>〇There is a possibility that expansive soil is affecting the pavement. |
| Problem Soil Measures | 〇Unsuitable soil is removed and replaced by suitable soil material.<br>〇Soil treatment with mixing cement, lime or some other materials for unsuitable materials<br>〇Nonwoven geotextiles |
| Expected Technological Demands from Japan | 〇Research cooperation between industry, government and academia, including building and updating databases, distribution maps, guidelines, etc. regarding problematic soils.<br>〇Soft soil treatment methods, slope protection technologies |

| Survey Item | Description |
|---|---|
| ***Ghana*** | |
| Problem Soil | Black cotton soil (Expansive soil), Weathered muddy shale, Amphibolite and Schist of the Dahomeyan Group, Phyllite, Dispersive laterite, Mica-rich soil materials, Soft soil (Swampland) |
| Standards/Manual | ○Insufficient description for problematic soils<br>○GHA design guide(1981)<br>○Highway Guideline assisted by JICA(2023)<br>○Road and Bridges Specification<br>○GHA National building code |
| Distribution Map | ○No distribution map for problematic soils<br>○Geological Map of Ghana (1:1,000,000) |
| Examples Encountered on Problem Soil | ○Cracks in houses caused by BCS<br>○Shale in the Central Region changes into muddy material due to moisture<br>○Gully erosion on phyllite cut faces<br>○Large settlements caused by muddy phyllite materials due to seepage water<br>○Lack of CBR/strength and large settlement due to mica-rich soil materials<br>○Damage caused by rippling of roads on soft soil in swamp areas |
| Problem Soil Measures | ○Unsuitable soil is removed and replaced by suitable soil material<br>○French Drainage ○Geotextile<br>○Soil treatment with mixing cement, lime or some gravel materials<br>○Ground improvement using stone columns<br>○Geomembrane protection to prevent muddying of Phyllite |
| Expected Technological Demands from Japan | ○Cooperation between government and academia regarding problem soil<br>○Create databases including technology for document management and soil quality.<br>○Creation of technical standards, etc.<br>○Application of geo-reinforcement materials (including geosynthetics, polymers, chips, etc.) |

*Source: JICA Study Team*

The overall summary of the field survey results is shown in Table 5.2.6. Problem soils in the target countries were mainly expansive soil, dispersive soil and laterite. While 5 of 13 target countries visited have standards or manuals referring to problem soils, distribution assumption maps were not developed in most countries.

Table 5.2.6 Overall summary of overseas field survey

| Target Country | Major problem soil | Standards/Manuals | Distribution Map |
|---|---|---|---|
| Cambodia | Dispersive soil | No | No |
| Indonesia | Expansive soil, Peat | Yes | Yes |
| Thailand | Expansive soil, Dispersive soil | No | No |
| Kyrgyzstan | Dispersive soil (Loess) | No | No |
| Tajikistan | Dispersive soil (Loess) | No | No |
| Palau | Coral sand/gravel | No | No |
| Marshall Islands | Coral sand/gravel | No | No |
| Ethiopia | Expansive soil, Laterite | Yes | Yes (under study) |
| Kenya | Expansive soil, Laterite | Yes | No |
| Tanzania | Expansive soil, Laterite | Yes | No |
| Guinea | Laterite | No | No |
| Côte d'Ivoire | Laterite | No | No |
| Ghana | Expansive soil, Laterite | No | No |

*Source: JICA Study Team*

# CHAPTER 6. PREPARATION OF HANDBOOK FOR PROBLEMATIC SOIL MEASURES

This chapter describes the preparation of the handbook for problematic soil measures for developing countries, where the risk of encountering problem soils in construction work is a concern. This handbook aims to reduce risks and ensure quality in construction works funded by JICA's Grant Aid and Yen Loans. It is intended to be referred by government counterparts, construction consultants and contractors in developing countries problem soils are distributed, as well as JICA staff, Japanese construction consultants and contractors engaged in infrastructure and building projects in such countries.

The handbook covers basic concepts of risk management for problem soil along with foundational knowledge about them. It comprehensively addresses solutions and countermeasures for widely distributed problem soils such as Expansive soil, Dispersive soil, Collapsing soil and Laterite during planning, design, construction, and maintenance phases as far as possible. Additionally, it provides an overview of problem soils other than the aforementioned to raise awareness of them. The appendices of the handbook include criteria for identifying expansive soils based on their soil properties, chemical indices for identifying expansive and dispersive soils, test standards, maps showing the global distribution of these soils, regional/country-specific distributions of these soils, various classification systems related to soils, a Q&A section, case studies, lists of symbols and abbreviations, and references.

These materials are based on literature research and field surveys conducted in developing countries as part of the project. The handbook is intended to offer guidance and information to project implementers and engineers when facing issues related to problem soils. However, it is important to note that this handbook is not a guideline or technical standard. Therefore, the final decision-making for problem-solving lies with the project implementers and engineers.

# CHAPTER 7. PROBLEM SOIL MEASURES

Based on literature research and field survey results from developing countries, this chapter summarizes the characteristics, origin, formation process, distribution, identification methods, engineering issues, and countermeasures for each type of problem soil. Countermeasures of some problem soil are excluded due to limited information..

For further detailed information, refer to "Handbook for Problematic Soil Measures Chapter 2 & Chapter 3" of this project.

## 7.1 EXPANSIVE SOIL

Expansive soil absorbs moisture during the rainy season, causing it to swell, and loses moisture during the dry season, leading to shrinkage. Many soils contain expansive clay minerals such as smectite, which absorb water. The swelling and shrinking are not completely reversible; cracks that form during the dry season allow water to enter during the rainy season, and the resulting swelling pressure can cause shearing and disturb the soil. The thickness of expansive soil can reach up to 20 meters, but the problematic depth is typically the active zone, which is usually around 3 meters.

- Factors Influencing Swelling and Shrinking:

  Swelling occurs due to changes in moisture content. Changes in the amount of water or its chemical composition alter the inter-particle force field, leading to shrinkage or swelling. Key factors influencing swelling include soil properties like clay mineralogy, soil chemistry, water retention, plasticity, soil structure, and dry density. Environmental factors include initial moisture conditions, moisture fluctuations (such as climate, groundwater, drainage, vegetation, permeability, and temperature), and stress conditions (such as stress history, site conditions, load bearing, and soil profile).

- Origin and Parent Material:

  Expansive soils form from various parent materials, including alluvial deposits, colluvial deposits, lake deposits, marl, limestone, basic igneous rocks, metamorphic rocks, and volcanic rocks. Most black clays in tropical Africa are residual products formed by the weathering of basic rocks like basalt, while black cotton soil (BCS) in India is primarily found over Deccan basalt. Unlike the BCS, expansive soils in Indonesia originate from parent materials like claystone and clay shale from sedimentary rocks. Parent materials for expansive soils include basalt from volcanic rocks, claystone and clay shale from sedimentary rocks, and schist and gneiss from metamorphic rocks, as well as volcanic ash. Expansive soils do not typically develop in acidic soils.

- Clay Minerals:

  The characteristics of expansive soils are controlled by the clay minerals they contain, e.g. smectite minerals such as montmorillonite which are highly expansive. Clay minerals are categorized by their layered structure into kaolin, mica clay minerals, smectite group minerals, and mixed-layer minerals. Bentonite is a representative smectite material. Clay minerals have the highest free swelling rate in $Na^+$ montmorillonite and $Na^+$ hectorite, with greater expansiveness resulting from higher $Na^+$ content.

- Formation Process

  The general soil formation process for Vertisols, a typical expansive soil classification, includes: cracking and swelling, self-mulching, churning, slickenside, sphenoid and bowl structures, Kankar formation, dark coloration, formation of smectite clay, and clay translocation.

Expansive soil is known by various names, such as Black Cotton Soil (Regur) in India. Other names for expansive soil include Margallitic Soil (Indonesia), Chernozem (Central Africa), Badob Soil (Sudan), Vlei Soil (South Africa), Tir (North Africa), Barros (Portugal), Smonitza/Smolnitza (Balkans), Black Soils (Australia), and Grumsol (USA).

Expansive soil is widely distributed across the world, especially in arid and semi-arid regions, as well as areas that experience wet conditions (rainy season) after prolonged droughts (dry season). Their distribution varies based on geology (parent material), climate, hydrology, topography, and vegetation. In many areas, evaporation rates exceed annual rainfall, leading to moisture deficits in the soil. As a result, the ground tends to expand when rain falls increasing the likelihood of heaving. In semi-arid regions, short rainfall periods followed by long dry spells can create seasonal cycles of expansion and contraction.

Countries with expansive soils include the U.S. (Texas, California), India (Deccan Plateau, Black Cotton Soil), Australia, Africa (central and northern Nigeria, Sudan Nile Basin, East Africa), South America (Orinoco River Basin, Venezuela), China (Sichuan Basin, parts of the Loess Plateau), and Europe (France). Distribution map of expansive soil is shown in Figure 7.1.1.

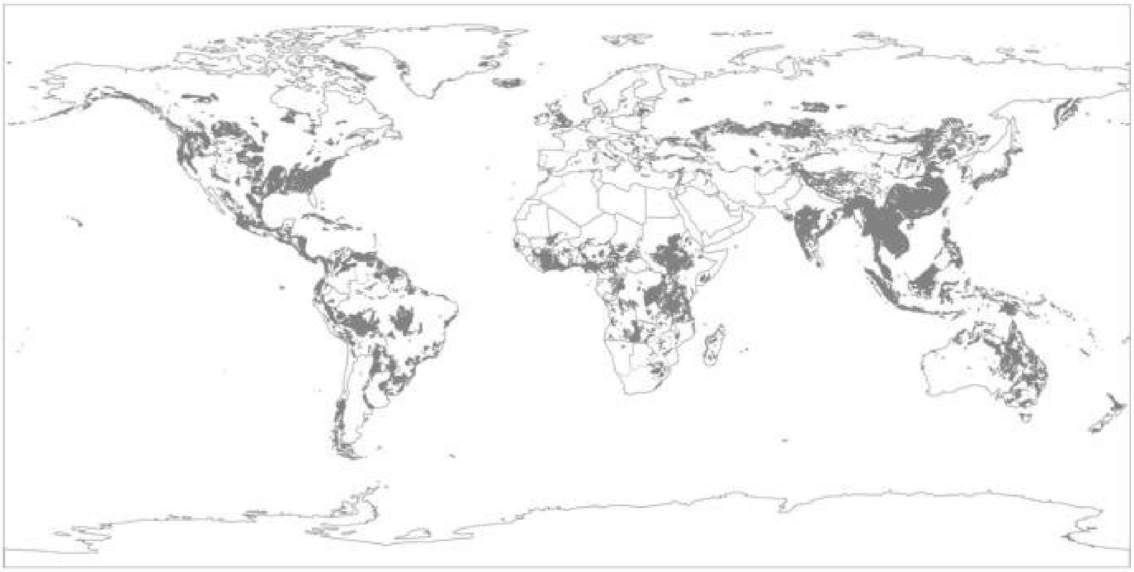


Figure 1 – Global distribution of shrink–swell soil where major construction costs occur (by region)

*Source: Swelling and shrinking soils, Jones, Lee; Banks, Vanessa; Jefferson, Ian. 2020*

Figure 7.1.1 Distribution map of expansive soil (Jones Lee, 2020)

Expansive soil is typically identified by tests measuring the amount of swelling and swelling pressure. However, due to limitations in sampling, cost and time, mechanical tests on all soil are not feasible. Simple on-site methods are used during site surveys, while lab tests are preferred in preliminary investigations. For suspected expansive soils, mechanical property tests are recommended. Refer to the handbook for detailed methods.

## 7.2 DISPERSIVE SOIL

Dispersive soils are clay-rich soils in which clay particles separate and disperse into water when exposed to relatively pure water. This occurs when repulsive forces between particles exceed attractive forces, leading to the breakdown of aggregation and the formation of a colloidal suspension. Unlike non-dispersive soils, dispersive soils do not have a threshold velocity to resist erosion—particles can become suspended even in still water, making the soil highly vulnerable to erosion and piping.

While dispersive and non-dispersive soils may have similar clay content, dispersive soils typically contain a higher amount of dissolved sodium in pore water (up to 12%). This high sodium content weakens the bonds between clay particles by expanding the diffuse double layer around each particle, increasing repulsive forces and causing dispersion. In contrast, high salinity with adequate calcium or magnesium can help maintain aggregation.

Erosion in dispersive soils is influenced by several factors, including:

- Type of clay minerals
- Exchangeable sodium percentage (ESP)
- Salt concentration (ECe)
- pH and organic matter
- Moisture content and temperature
- Type and concentration of pore water ions

Common indicators of dispersive soils include:

- Clay content > 30%
- ESP > 5
- Electrochemical Stability Index (ESI) < 0.02–0.05
- ECe > 2 dS/m
- Low organic matter
- Presence of illite or sodium-rich montmorillonite

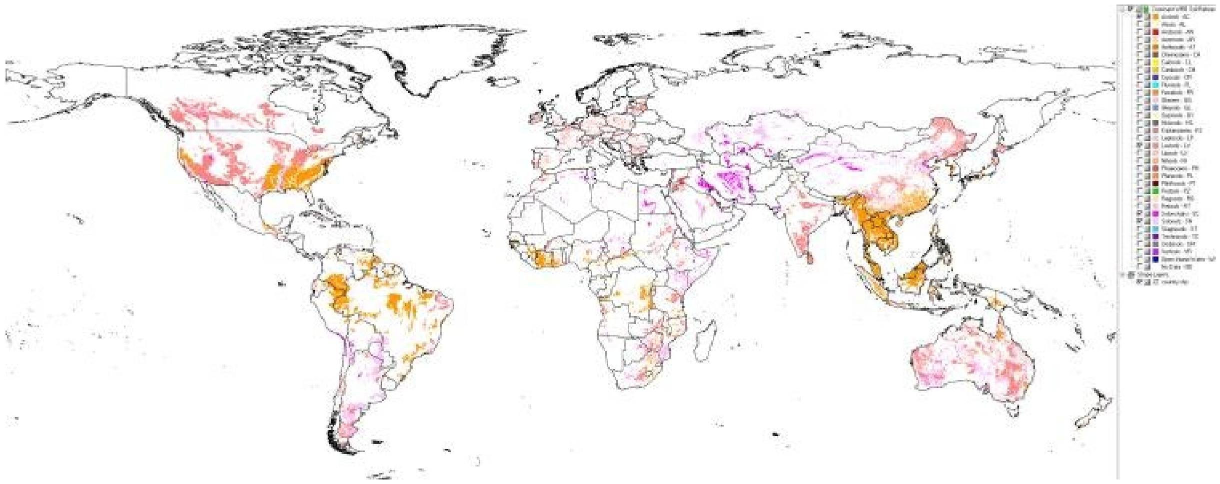
Soils with high montmorillonite content are generally expansive while they may also be dispersive if sodium is dominant. However, dispersity is not solely determined by mineralogy; for example, montmorillonite-free soils can still disperse if sodium levels are high.

Proper identification and treatment of dispersive soils are essential to prevent erosion, piping, and structural failures.

The global distribution of dispersive soils has not been comprehensively documented in existing literature. However, such soils have been reported in various countries, particularly in regions characterized by river basins, floodplains, and wetlands. Examples include Cambodia (alluvial deposits in the Mekong River and Tonle Sap Lake basins), Australia (notably in Tasmania), northeastern Thailand, South Africa (Senekal Dam), the United States (Great Lakes region and prairies), Greece, India (humid regions and river basins), Latin America, Indonesia (Java and Sumatra), Zimbabwe, China (Yangtze and Yellow River basins), Bangladesh (Ganges and Brahmaputra Delta), Nigeria (Niger and Benue River basins), Israel (Mediterranean coastal region and Jordan River basin), as well as Iran, Spain, Ukraine (from the Black Sea to the Chernobyl area), Brazil, New Zealand, Mexico, and Vietnam.

According to the Harmonized World Soil Database (HWSD), the soil types most likely to exhibit dispersity include Solonetz and Solonchak. Vertisols, typically classified as expansive soils, can also become dispersive when sodium content is high, although this has mainly been reported in Australia. Other soil types which are potentially dispersive are Luvisols, Acrisols, and Alfisols. Considering the widespread presence of dispersive soils in Cambodia, Acrisols are especially assumed to have high dispersive potential.

To identify potentially dispersive soils in a given area, it is recommended to consult the SMU (Soil Mapping Unit) table in the HWSD and examine the Exchangeable Sodium Percentage (ESP). Soils with ESP values exceeding 15% are considered highly dispersive, while those with ESP between 6% and 15% present moderate risk and warrant further attention.



*Source: HWSD Ver.2.0*

Figure 7.2.1 Distribution map of Solonetz, Solonchak, and Acrisols in the HWSD

There are four primary test methods for identifying dispersive clay. Among them, the pinhole test is considered the most reliable, followed by the double hydrometer test. While some researchers argue that chemical analysis provides higher accuracy than the double hydrometer test, it is less common in geotechnical practice due to limited familiarity with chemical testing among civil engineers. The crumb test is a simple screening method but lacks accuracy, making it suitable for preliminary assessments only. As no single method is definitive in all cases, using multiple tests in combination is recommended if possible. As the pinhole test requires specialized equipment, only a limited number of laboratories are able to perform it. At the very least, the double hydrometer and crumb tests should be carried out. If available, chemical analysis should be carried out in a laboratory equipped for such testing. To ensure reliable results, soil samples must be collected and stored at their natural moisture content level. Samples should be sealed in moisture-proof containers during shipment and storage.

### 7.3 LATERITE

Laterite is a soil rich in iron and aluminum, typically formed in hot and humid tropical regions. Due to its high iron oxide content, it characteristically appears in a rust-red color. Laterite forms through the intense and prolonged chemical weathering of the parent rock during alternating wet and dry seasons. This process is known as lateritization. This tropical weathering significantly alters the thickness, particle size, chemical properties, and mineral composition of the soil.

Historically, laterite was quarried and shaped into blocks for construction purposes. In Southeast Asia, monuments such as Angkor Wat—constructed after the year 1000—used laterite along with bricks and stone. The Prasat Preah Toes Bridge, located approximately 60 km east of Angkor Wat, is a stone bridge built from laterite during the late 12th to early 13th centuries and remains in use today as part of National Road No. 6.

Laterite has been identified as a problem soil based on experiences in India, Africa, the United States, and Australia (Wooltorton, 1975). Terzaghi also noted that the "red soil" at Kenya's Sasumua Dam exhibited dramatic changes in Atterberg limits when oven-dried before testing, highlighting that laterite behaves differently from conventional soils and should be categorized as a problem soil.

Laterite is primarily found in tropical and subtropical regions, with most of its distribution occurring between 35°N and 35°S latitude. The distribution map of laterite is shown below. The countries where laterite is commonly found include those in Africa (such as Ghana, Nigeria, Ivory Coast, Cameroon, Republic of the Congo, Angola, Kenya, Uganda, Tanzania), Asia (including India, Sri Lanka, Thailand, Vietnam, Cambodia, Laos, Malaysia, Indonesia), Australia, South America (Brazil, Colombia, Venezuela), and Central America and the Caribbean (Mexico, Cuba, Jamaica, Haiti, Dominican Republic), as well as Papua New Guinea.

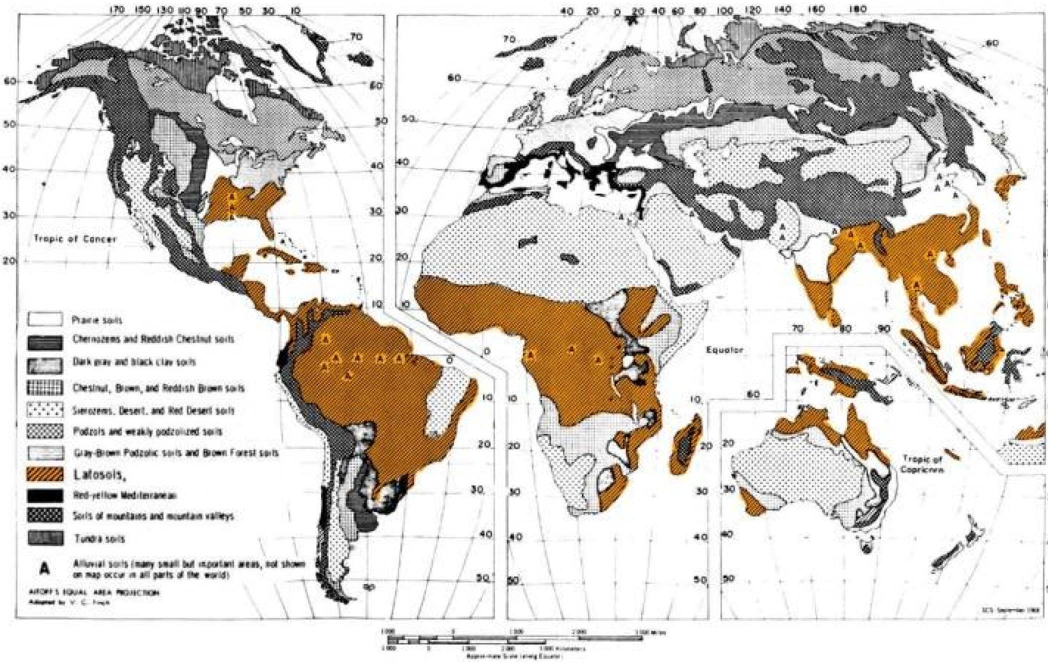



*Figure 2.6: Latosol soil (collective laterite) world distribution (http://www.nzdl.org)*

*Source: AN INVESTIGATION INTO THE GEOTECHNICAL ENGINEERING PROPERTIES OF LATERITE SOILS IN NILAI, MALAYSIA, Ahmed Sujeeth （2015）*

Figure 7.3.1 Distribution map of laterite

Laterite can be used as road material if it is of good quality. However, in some cases, the quality of the soil worsens with depth. When the soil quality is poor, replacement methods are used, and if suitable replacement materials cannot be obtained, stabilization treatment methods are considered. Since laterite has better ground properties than weak soil with extremely low N-values, deep mixing methods commonly used for weak soils are not applied. However, when implementing Japanese ground improvement methods, it is necessary to import construction machinery and improvement materials which may pose challenges, as transportation time and import procedures can affect the application of construction technology.

- Replacement Method

The replacement method is the most common solution for laterite. It is cost-effective, easy to implement, and helps shorten construction periods, as there are quality materials within the laterite that can be used. However, there is no standard design method for the thickness of replacement layers, and empirical methods are used depending on the region. In cases where there is a limited amount of high-quality laterite, a mixture of good and poor-quality laterite may be used. Even if the surface layer of the laterite is hardened, the layers beneath tend to be finer and have lower strength, leading to weaker soil layers. If the thickness of the replacement is too thin, deformation issues may arise after the road is in use. Therefore, in some countries in West Africa, countermeasures such as placing crushed stone at the excavation bottom are applied.

- Stabilization Treatment Method

The application of stabilization treatment methods in road construction has been widely adopted by many countries over the past few decades. These methods, designed to improve road performance, are summarized in Table 8.3.17. When using these methods, it is advisable to select an appropriate technique by conducting laboratory tests to determine the optimal mix proportions, followed by trial construction, particularly when local materials are available at low cost in the region.

## 7.4 COLLAPSIBLE SOIL

Collapsible soils are naturally formed through geological and geomorphological processes or resulting from human activities. These soils have an open structure and semi-stable structure, and experience more rapid volume changes than during consolidation. In the initial stages, particles with low cohesion form large voids and are in a dry state. Collapsible soils are commonly found in arid regions, where the dry environment promotes their formation. In nature, they form from debris flows, wind-blown sediments, cemented high-salinity semi-stable soils, and tropical residual soils. They can also form in poorly compacted or discarded soils. These soils have low density and become relatively hard and strong when dry.

Collapsible soils cover about 10% of the world's surface, with five major loess regions: the Midwest of North America, South America, Europe (including Germany, Eastern Europe, and Western Russia), Central Asia, and China. Other regions include Nigeria, Kazakhstan, Australia, South Africa, Rhodesia, Egypt, and Iran. These areas often coincide with densely populated regions or key underground infrastructure, making them vulnerable to collapse, which has become an emerging issue. The most concerning areas are Eastern Europe, Russia, and expanding parts of China.

The global distribution map of collapsible soils is shown below. Soils considered to be collapsible in the HWSD are Andosols, Arenosols, Calcisols, and Gypsisols.

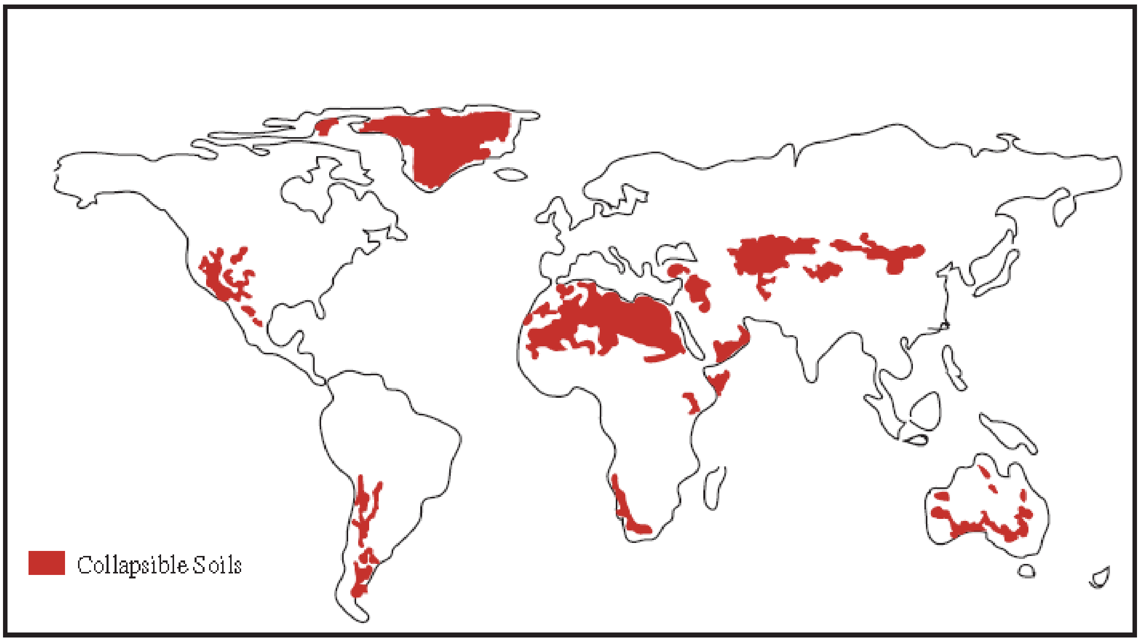
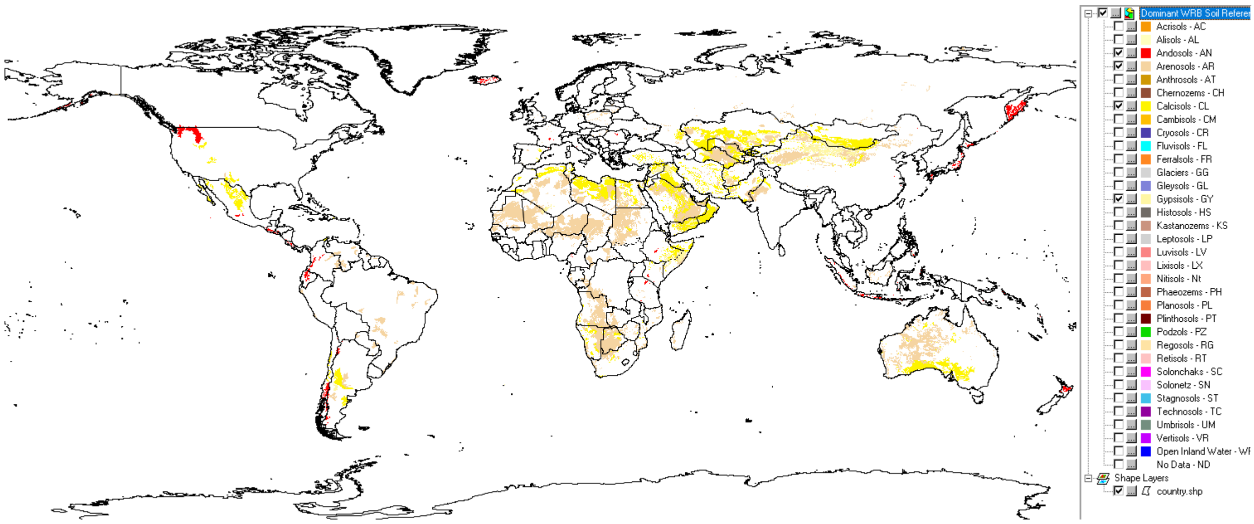



Figure 1.1: World distribution of collapsible soils, modified after [FAO, 1990].

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

Figure 7.4.1 Distribution map of collapsible soil




*Source: HWSD Ver.2.0*

Figure 7.4.2 Distribution map of collapsible soil estimated from the HWSD (Andosols, Arenosols, Calcisols, Gypsisols)

## 7.5 EROSIVE SOIL

Erosive soils are composed of geological materials that can easily be deformed or moved as a result of natural weathering and erosion processes. These soils are vulnerable to external forces like wind, water, ice, and gravity, which can lead to instability. Erosive soils are a significant concern in agriculture, construction, and environmental protection. These soils have several key characteristics. They are highly susceptible to erosion and have high permeability, which allows water to easily infiltrate and wash away the soil.There is also low cohesion between soil particles, leading to structural instability. Furthermore, these soils weather quickly, causing the rapid decomposition of soil and rock. Sandy soils and sandy silts, which have weak particle cohesion, are particularly susceptible to erosion. Additionally, dispersive soils, collapsible soils, and soils with high clay content or strong cohesion, such as saline, calcareous, and sulfate soils, are also highly susceptible to erosion. Soluble soils dissolve in water, but they erode more slowly over geological time scales, which makes them different from erosive soils.

Erosive soils include various types of special soils and are widely distributed across the globe. The following figures show the global distribution of soil erosion.

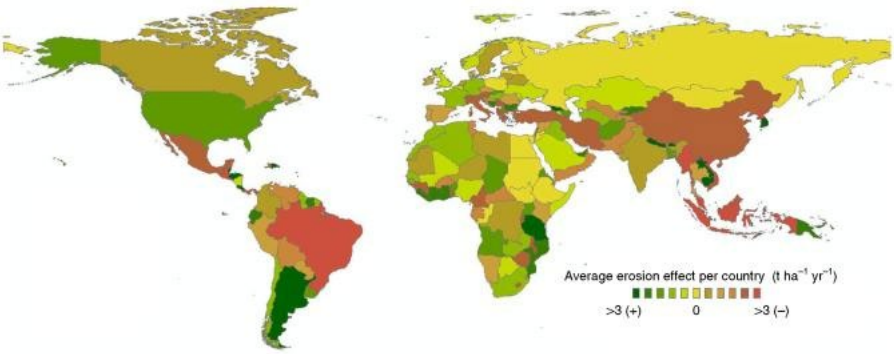
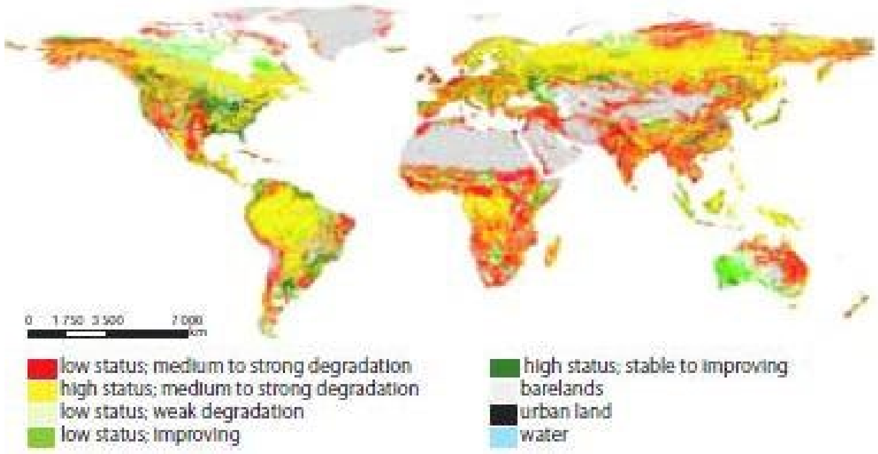



**Fig. 3 | A global map of countries' soil erosion performance.** The map is based on soil erosion discontinuities between each country and all of its neighbours (unweighted). Darker green indicates that a country has a more positive impact on the global rate of soil erosion than its neighbours (that is, it has a dampening effect), and darker red indicates that a country has a more negative impact on the global rate of soil erosion (that is, it has higher erosion rates). For all countries that perform more poorly than their neighbours, the map shows how much soil erosion they could mitigate (per hectare and year) just by catching up to their neighbours. Even the better performing countries could probably further improve their impact, so this map probably presents a lower bound for countries' erosion mitigation potential—especially in regions where soil erosion is high. For reference, the global average soil erosion rate is 2.4 t ha$^{-1}$ yr$^{-1}$, and we estimate the average country discontinuity at 1.4 t ha$^{-1}$ yr$^{-1}$.

*Source: Countries and the global rate of soil erosion, David Wuepper, Pasquale Borrelli, Robert Finger（2020）*

Figure 7.5.1 Areas of soil erosion (1)




*Source: Biochemical soil treatment for erosion control against Desertification, I. Chang, J. Im, H.D. Shin, G.C. Cho（2015）*

Figure 7.5.2 Areas of soil erosion (2)

A simple method for evaluating soil erosion was proposed by Roslan and Mazidah (2001), who classified the degree of soil erosion using the percentage of sand, silt, and clay in soil samples through the ROM scale. Hudson's (1979) soil erodibility (K-factor) method classifies soil erosion using particle size distribution. The classification of soil erosion based on the ROM index is shown in Table 7.5.1.

Table 7.5.1 Classification of soil erosion based on ROM

| ROM-scale | Soil Erosion Classification |
|---|---|
| <1.5 | Low |
| 1.5~4.0 | Moderate |
| 4.0~8.0 | High |
| 8.0~12.0 | Very High |
| >12 | Extreme |

*Source: Erosion risk index: Correlation of ROM-scale and Mackintosh Probe at Sungai Langat Tributary, Nazreen Farina Ahmad Sabri1 et al. (2022*

## 7.6 CRUSHABLE SOIL

Crushable soils consist of particles that are fragile, and when external forces are applied, the particles break, causing deformations such as settlement. Materials that are considered crushable include volcanic deposits like pumice and scoria, weathered residual soils like ash, and marine deposits such as limestone sand or coral gravel. These materials are characterized by unique particle shapes, fragile surfaces, and inherent particle brittleness, making them prone to crushing. Even materials used in large structures which are relatively firm such as fill dams may experience particle crushing under high load pressures. Geotechnical materials, depending on the magnitude of external forces, can cause particle breakage. Therefore, it is crucial to establish an indicator for crushability and compare it with the external force conditions encountered to address crushability effectively in engineering problems.

Crushable soil is found in regions such as tropical coastal areas, volcanic zones, and regions with intense weathering. These soils include volcanic ash soils rich in pumice, sandy soils derived from coral reefs and shells, gypsum in carbonate soils, weathered granite, chalk, and rock salt. Karst topography, although considered soluble terrain, is also sometimes categorized as crushable soil. According to the HWSD, soils that are likely to be crushable include sandy and loamy Cambisols, sandy Arenosols, underdeveloped Regosols, and Andosols, which contain high amounts of pumice made from volcanic ash. Luvisols, which exhibit developed granular structure, may also be susceptible.

The determination of crushable soils is based on the changes in particle size distribution after a shear test. This involves examining changes in the uniformity coefficient (Uc) and the curvature coefficient (Uc'), as well as comparing the particle size distribution curves before and after the shear test.

## 7.7 SOLUBLE GROUNDS

Natural soluble rocks include limestone (which also encompasses dolomite and chalk), gypsum (including anhydrous gypsum), and salt (rock salt), listed in order of their solubility and occurrence. In general, underground cavities form when these soluble rocks are exposed to rainwater, river water, or groundwater, which can lead to the risk of collapse or subsidence. The terrain formed by soluble rocks typically involves watercourses that have expanded through joints, cracks, stratification, and caves in the rock, which in turn leads to the flow of water underground. As a result, the surface is often dry, giving rise to unique karst landscapes, which include dry valleys and limestone pavements. Karst terrains are prone to various geological hazards, ranging from gradual subsidence to catastrophic collapses or sinkholes.

When soluble rocks are located within tens of meters from the surface (sometimes even deeper), they can lead to various geological disasters. The dissolution of rocks is generally not rapid enough to cause immediate collapse of structures. However, in the case of salt, considering a design life of 50 to 100 years, it can completely dissolve within that period. The dissolution of limestone is much slower in comparison, often taking thousands of years to affect the structures built on top of it.

Karst terrain primarily composed of limestone is distributed worldwide. In terms of topographical classification, 40% of karst terrain is found in mountainous areas, while 30% is found in plains and plateaus, respectively.

As for measures before construction to cope with Soluble Grounds, small cracks should be filled with soil and compacted. If the soil does not penetrate deep into rock cracks, grouting should be performed. If this does not suffice, shallow foundations, rigid mats, or foundations spanning cavities should be constructed, along with deep foundations such as piles or piers. If the soil cover is thin, it is recommended to either place shallow foundations on the bedrock or artificially raise the soil on top of the bedrock. For heavy structures that are prone to settlement, pile foundations are typically chosen when the bedrock is deep.

For ground improvement, the heavy weight drop method can be used. The pattern of ground deformation during dynamic compaction helps identify areas prone to sinkholes or instability, which can then be addressed. If settlement progresses with multiple drops of heavy weight, it suggests that voids remain deep, and concentrated grouting can be used as a countermeasure. When the bedrock is deep and the affected area is extensive, grouting can be injected into most of the voids. If the bedrock is shallow and there is no groundwater, the soil can be removed down to the bedrock surface, then geogrids or geotextiles can be laid down, and finally good-quality material can be filled on top to form a foundation for the structure.

## 7.8 PEAT

Peat is a type of organic soil formed in wetlands or marshes. It is created through the accumulation and decomposition of plant remains and organic matter under waterlogged conditions, where oxygen is limited. Due to its high water content, low strength, and large void ratio, peat can cause settlement or sliding failure in embankments.

Peat is known to occur in the Arctic and subarctic regions while it can also be found in tropical and temperate wetlands. In tropical regions, peat formation is slower and sometimes roots or trees remain without undergoing weathering. This can pose construction challenges when excavation is required.

Organic soils are classified based on their organic content. Peat, one of the highest organic matter soils, consists of partially or fully decomposed plant remains and accumulated organic matter (less than 25% by the weight of mineral material) in a saturated state. Peat has a spongy consistency, a distinct organic odor, and a color ranging from brown to black.

The elemental composition of peat varies depending on the plant composition and degree of decomposition. Peat is recognized as a highly porous material with low shear strength and high compressibility, related to its very high moisture content (over 200%) and organic content (over 75%).

The properties of peat depend on its plant composition, fiber content, and the degree of decomposition of the plant remains. The degree of decomposition can be classified using the Von Post scale. Peat is classified into ten stages, with H1 being the least decomposed and H10 being the most decomposed. The degree of decomposition according to the Von Post scale is determined by visual inspection of the peat structure and the results of compression tests.

Peat is found all over the world, covering approximately 5% to 8% of the Earth's land surface. It occurs in countries in temperate and subarctic regions such as Canada, Finland, Sweden, Norway, and others, but 8% to 11% of the world's peat is located in tropical or subtropical regions. Peat is also present in countries such as the United States, China, Germany, and Poland.

The main regions where peat is distributed include the United States (e.g., Florida: Everglades wetlands, Louisiana: Mississippi River Delta, Minnesota, Wisconsin, Michigan: wetlands around the Great Lakes), Canada (wetlands around Hudson Bay and northern regions), Brazil (Amazon Basin: wetlands and lowlands in tropical rainforests), Argentina (wetlands in the Pampas region), Finland, Sweden, Norway, the United Kingdom, Ireland, Russia (wetlands and peatlands in Western Siberia), the Democratic Republic of Congo (Congo Basin wetlands), Nigeria (Niger Delta region), Indonesia (wetlands and peatlands in Sumatra and Borneo), Malaysia (Sarawak and Sabah states' wetlands), China (Yangtze and Pearl River Delta wetlands), Australia (wetlands and peatlands on Tasmania), and New Zealand (wetlands on the North and South Islands).

The countermeasures for peat are already published in Japan as the "Peat Soft Ground Countermeasure Construction Manual." In developing countries, this manual can also be referenced for considering countermeasures. The manual is a valuable resource not only for countermeasures but also for other related matters.

### 7.9 SALINE SOIL

Saline soils, saline-sodic soils, and sodic soils are types of salt-affected soils. They are widely distributed around the world, covering about 33% of irrigated land and 20% of arable land globally.

Salinity is measured by the electrical conductivity of the saturated extract (ECe), while sodium content is determined by the exchangeable sodium percentage (ESP) or sodium adsorption ratio (SAR). The characteristics of each soil type are as follows:

According to the 2000 FAQ report, the total area of salt-affected soils is 932.2 million hectares, with saline soils covering 351.5 million hectares and sodic soils covering 581 million hectares. However, the total area of salt-affected soils worldwide, including both saline and sodic soils, is 831 million hectares. These soils are distributed across all continents, including Africa, Asia, Australia, and the Americas. Based on the FAQ/UNESCO World Soil Map, the total area of saline soils is 397 million hectares, and the total area of sodic soils is 434 million hectares. The majority of lands affected by salinity are found in dry and semi-dry environments.

The regions where they are found include the Aral Sea Basin in Central Asia (Amu Darya and Syr Darya river basins), the Indo-Gangetic Basin in India, the Indus River basin in Pakistan, the Yellow River Basin in China, the Euphrates River Basin in Syria and Iraq, the Murray-Darling Basin in Australia, and the San Joaquin Valley in the United States.

Saline soils can be identified through both visual symptoms and chemical testing. Field symptoms of salinity may include patchy leaf burn on crop fields, the presence of salt-tolerant plants, increased soil moisture in semi-arid or arid areas, irregular growth patterns in crops with a lack of vitality, exposed areas with scalded burns, and the presence of white spots, streaks, or crust on the soil surface. In the early stages of salinization, one or more of these symptoms may appear, though there could be no visible signs at all. Typically, soil and plant symptoms occur in the later stages of salinity damage, where remediation requires time and significant cost.

For chemical testing, salinity classification requires the measurement of electrical conductivity (ECe), exchangeable sodium percentage (ESP), and sodium adsorption ratio (SAR). The concentrations of cations such as Na+, Ca2+, and Mg2+ and the cation exchange capacity (CEC) of the soil are required to calculate ESP and SAR.

### 7.10 SULFATE/SULFIDE SOIL

Although present in small quantities, sulfides and sulfate minerals in the soil can cause serious agricultural and environmental problems. Sulfate soils are soils that contain a high amount of sulfate ions ($SO_4^{2-}$). Representative sulfates include calcium sulfate (gypsum: $CaSO_4$), magnesium sulfate (Epsom salts: $MgSO_4$), sodium sulfate (soda), and iron sulfate. Sulfide soils, on the other hand, contain a high amount of sulfides ($S^{2-}$). Typical sulfides include iron disulfide ($FeS_2$, pyrite) and zinc sulfide (ZnS). Sulfide soils usually form in wetland or low-oxygen (reductive) environments, where sulfate ions are reduced to form sulfides.

Sulfate/Sulfide soils are found on at least 24 million hectares of land surface or near the surface worldwide. They have a wide climatic and geographical distribution, but they are most found in tropical and coastal regions. These soils are typically found in arid and semi-arid areas. Major countries where sulfate soils are distributed include the United States (Great Basin, Death Valley, Salt Lake region), Argentina (Pampa region), Bolivia (Uyuni Salt Flats), Egypt (Nile Delta region), Tunisia, Algeria, Morocco, Saudi Arabia (inland desert areas), Iran (Kavir Desert), Kazakhstan (Caspian Sea coast), Uzbekistan (around the Aral Sea), and Australia (South Australia, New South Wales).

### 7.11 CARBONATE SOIL

Carbonate soils are soils that primarily contain carbonate minerals such as calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$), and are widely distributed, especially in arid and semi-arid regions. Depending on the formation conditions, they can range from hard rocks, gravel, sand, clay, and silt to very fine and loose materials. As a result, there is considerable uncertainty and variability in the characteristics of these soils. Soils formed from weathered limestone or carbonate mineral particles generally have a relatively firm surface. Coral soils are also included as carbonate soils and may eventually transform into limestone with geological aging. Synonyms for carbonate soils include lime soils, marl soils, and calcareous soils. Lime soils, which contain a significant amount of calcium carbonate, are treated as soluble ground.

Carbonate soils are primarily found in arid and semi-arid regions. Although there is no specific distribution map for carbonate soils, there is a distribution map for the parent material, carbonate rocks. Key regions where carbonate soils are found include the United States (in dry regions such as California, Nevada, Arizona, New Mexico, Texas, and the Great Basin, particularly Utah), Mexico, Argentina (Pampa region and Patagonia), Peru (Andes Mountains), Spain, Italy, Greece, Ukraine, southern Russia, Morocco, Algeria, Tunisia, Libya, Egypt, Ethiopia, Kenya, Tanzania, Saudi Arabia, Iran, Kazakhstan, Uzbekistan (around the Aral Sea), India (Thar Desert), and Australia.

Marl soils, on the other hand, are typically deposited in aquatic or wet environments, often found at the bottoms of rivers, lakes, or shallow marine areas. These soils are widely distributed in Europe (Paris Basin, Jura Mountains), North America (Appalachian Mountains), the Middle East (Nile River), South America (Patagonia), and Asia (Loess Plateau).

### 7.12 ACIDIC SOIL

Soil is a highly heterogeneous material, hence its pH cannot be measured as precisely as that of a pure solution. A soil with pH of 6.6 to 7.3 is considered neutral. Typically, the pH of soil ranges from 4 to 10. The ideal pH for agricultural soil is approximately 6.0 to 7.0.

Soils with a pH below 6.5 are referred to as acidic soils. The acidity of soil can be categorized into three types: active acidity, exchangeable acidity, and non-exchangeable acidity (or titratable acidity). Active acidity refers to the H+ ions in the soil solution that determines the pH. Exchangeable acidity, also called potential acidity, is measured in cmole (p+/kg) and consists of H+ ions and Al3+ ions adsorbed to clay particles or organic matter. Titratable acidity arises from the dissociation of weakly acidic functional groups in soil organic matter and the deprotonation of hydroxylated silicates. The higher the proportion of exchangeable aluminum and hydrogen, the lower the pH and the higher the soil's acidity. According to USDA and NRCS (1998), soils are classified based on their pH.

Acidic soils are primarily distributed across two global belts. The northern belt is characterized by cold and humid temperate climates, while the southern tropical belt features warm and humid conditions. In the colder and temperate regions, acidic soils are predominantly Spodosols, Alfisols, Inceptisols, and Histosols, whereas in the tropical regions, Ultisols and Oxisols are the dominant soil types.

Acidic soils pose significant challenges in agriculture, but in engineering, the primary concern lies with their high acidity, especially in acid sulfate soils. These soils can corrode buried concrete, pipelines, and reinforced foundations, thereby reducing the service life of structures. Under acidic conditions, heavy metals such as cadmium, lead, and zinc are more readily leached from the soil, potentially contaminating groundwater and rivers and causing water pollution. A notable example is the Carsington Dam in the United Kingdom, where acidic sulfate clay soil left in the foundation oxidized under intense rainfall during construction, resulting in a loss of strength and a subsequent slope failure.

### 7.13 CORAL SOIL

Coral soil is classified as soil derived from coral, a type of calcareous deposit. This includes both coral gravelly soil containing fragments of coral debris and soil layers primarily composed of coral reefs or coral rock. In general, coral has an internal porous structure, resulting in high porosity, high water absorption, and relatively low density. However, over time, processes such as precipitation and recrystallization lead to increased density and reduced porosity, transforming the material into stronger forms such as coral reefs and coral rock. Coral soil is composed of a mixture of coral with sand, silt, and clay.

Calcareous deposits consist mainly of calcium carbonate ($CaCO_3$), which originates from the shells and skeletons of benthic organisms such as corals, mollusks, and calcareous algae. Coral reef rock is a stratum of calcium carbonate formed by living marine plants (coralline algae) and marine animals (corals). As time passes, precipitation and recrystallization increase the density of the coral, eventually forming rock-like coral reef structures. Detailed mineralogical analyses using X-ray diffraction have shown that in geologically younger coral rock, $CaCO_3$ is entirely in the form of aragonite, while older coral rock typically contains calcite. The proportion of calcite increases with the age of the coral formation.

In island nations, coral is often used as concrete aggregate due to limitations in available construction materials. However, there are few studies on the properties of coral aggregate concrete, such as strength, durability, and mix design, and the development of appropriate mix designs for coral aggregate concrete is urgently needed. When using coral soil as aggregates, it is important to recognize that it possesses characteristics different from those of conventional aggregates. Because coral has an internal porous structure and a high water absorption rate, moisture management in fresh concrete becomes critical. Furthermore, its high permeability may affect the long-term durability of the concrete. On the other hand, due to its low density, the use of coral aggregate may contribute to reducing structural loads.

## 7.14 SAND WITH HIGH MICA CONTENT

In Bangladesh, load tests were conducted on bored piles, but the measured bearing capacity was significantly lower than the design bearing capacity estimated using N-values. To investigate the cause, detailed geotechnical investigations and laboratory tests including triaxial compression tests were carried out. These revealed mechanical properties that differed from commonly accepted expectations. This section summarizes a case study involving sand with high mica content.

Bangladesh lies at the confluence of the Ganges and Brahmaputra rivers, where a vast quantity of sediment has been transported over long distances from the Himalayas, forming lowlands that extend into the Bay of Bengal. Additional sediment is also supplied from the east by the Meghna River. In the city of Dhaka, the geological profile includes approximately 10 meters of alluvial clay at the surface, underlain by alternating layers of thin clay and thick sand deposits. These sand layers vary in grain size—fine, medium, and coarse—and are stacked in multiple strata that extend to depths exceeding 300 meters. Groundwater is extracted from these sand layers, resulting in a groundwater table that has dropped to below -40 meters in Dhaka, with annual declines of several meters.

Among the findings from field investigations in developing countries, interviews conducted in Ghana revealed two key issues associated with soils derived from mica-rich parent rocks. First, the compaction characteristics of these soils change significantly when water is introduced, leading to road settlement problems. Second, when mica-rich rock is used as aggregate in concrete, a decline in concrete quality has been reported.

The potential engineering issues related to soils containing mica are as follows:

- The bearing capacity tends to be lower than what is predicted by conventional bearing capacity formulas. Both end-bearing and shaft resistance may be reduced.
- Mica-bearing soils exhibit shear behavior similar to crushable soils; under drained shear conditions, they tend to deform on the compression side.
- When mica content exceeds 10%, the compaction characteristics deteriorate, and the compressibility increases, making such soils unsuitable for use in road pavement or embankments.
- With repeated compaction, particle breakage progresses, but beyond a certain number of cycles, further breakage ceases. At this stabilized stage, the deformation characteristics also become stable.

## 7.15 GLACIAL DEPOSITS (TILL)

Glacial deposits, also known as till, are widely distributed across temperate regions of the world, covering approximately 10% of the global land surface. Tills range from deformed basal layers that retain many of their original characteristics to mixed soils consisting of gravel, sand, silt, and clay, and in some cases, thin clay layers.

Till may undergo compression, shearing, reformation, and weathering under its own weight. It contains a wide range of particle sizes—from clay to boulders—and varies in composition from clay-dominated to rock fragment-dominated types. Tills may develop fissures and be deposited in layers, making it difficult to predict the specific characteristics of a given till at the time of construction. As such, till is considered a challenging material to work with in engineering projects.

## 7.16 ARID SOIL

Arid soils are formed under arid climatic conditions where annual evaporation exceeds annual precipitation, resulting in a persistent deficiency of soil moisture. It is estimated that approximately one-third of the Earth's land surface is currently in a state of aridity; however, only about 25% of these arid regions are composed of active sand dunes. Arid conditions are found in both hot and cold regions of the world, including hot deserts such as the Sahara and cold deserts such as the Gobi.

Soils formed under these conditions are generally referred to as arid soils and encompass a wide variety of types. These include desert soils, regosols (desert pavement soils), saline soils, alkaline soils, gypsiferous soils, calcisols, solonetz soils, and paleosols. Among saline soils, there are specific types known as salina, playa, and sabkha, which are categorized as problem soils due to their unique properties in high-salinity environments.

Although a distribution map specifically for arid soils is not available, Figure 8.16.1 shows the distribution of arid climates, which correspond closely to the presence of arid soils. Major regions where these climates—and thus arid soils—are found include the southwestern United States (such as Arizona, Nevada, New Mexico, and the Mojave, Sonoran, and Great Basin deserts in California and Utah), Mexico (Sonoran and Chihuahuan deserts), Chile and Peru (Atacama Desert), the Sahara Desert (covering parts of Egypt, Libya, Algeria, Mauritania, Mali, Niger, Chad, and Sudan), Namibia (Namib Desert), Botswana (Kalahari Desert), Saudi Arabia (Rub' al Khali Desert), Iran (Dasht-e Kavir and Dasht-e Lut deserts), the Syrian Desert (spanning Iraq, Jordan, and Syria), China (Taklamakan and Gobi deserts), India and Pakistan (Thar Desert), Australia (Great Victoria, Simpson, Tanami, and Great Sandy deserts), and Spain (Tabernas Desert).

Arid soils such as those found in desert regions are highly susceptible to wind erosion, which can lead to construction sites and roads becoming covered with sand. This can reduce work efficiency and cause visibility issues. Due to limited water availability in these areas, locally sourced water is most likely to be used; however, such water may contain high concentrations of dissolved salts, potentially affecting construction activities such as concrete placement. Even when wells are drilled for construction purposes, the supply of groundwater may be insufficient.

Soils like gypsiferous soils and Calcisols (calcareous soils) can exhibit high hardness, making excavation and processing difficult, which may increase construction costs and prolong project timelines. Additionally, alkaline soils and Solonetz soils may exhibit expansive behavior, leading to similar problems as those caused by expansive soils.

## 7.17 WEATHERED ROCKS AND METAMORPHIC ROCKS

Weathered rocks and metamorphic rocks can cause engineering problems before they transition into sedimentary materials and when they rapidly weather after excavation, leading to issues. Rocks undergo transformation into various types of soil depending on factors such as weathering susceptibility, mineral composition, and climatic conditions. Table 8.17.1 organizes the problems associated with rock types and weathered soils, their susceptibility to weathering, acidity, and related problematic soils.

Among sedimentary rocks, there are those that not only become problematic soils but also cause issues when used as embankment materials during the transition to medium or highly weathered rocks. Shale, for example, can serve as a good material for embankments, but due to the large voids between soil particles, it may experience weathering and subsidence after embankment construction. Additionally, weathering can be accelerated by rainfall, potentially leading to subsidence similar to that of collapsible soils, which requires careful attention.