Appendix (1)

Technology Transfer Manual

① Geophysical Prospecting

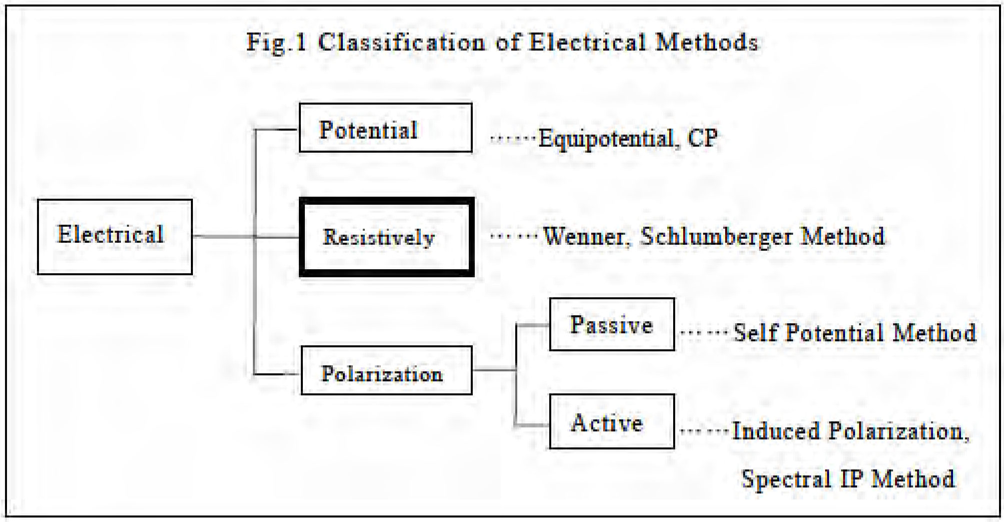
Technology Transfer Manual: Electric Prospecting (Resistively method)

1 Electric prospecting

Electric prospecting is a method for clarifying geological structure by utilizing differences between electromagnetic properties of rock and/or the phenomena that are naturally generated by these differences. Essentially, there are two types of electromagnetic properties of a substance, that is, relative resistance, and dielectric constant, but the most important of these for Electric sounding is the relative resistance of the rock.

Electric prospecting is used to survey man-made features such as dams, and geological features such as groundwater, ore veins, underground voids, landslides, and faults.

Figure 1 shows divisions of the Electric prospecting method



1.1 Polarization methods

Part of the underground structure has some sort of polarity. This provides the source for a naturally-occurring electrical current which can reach the surface, or the polarity conditions distributed underground can reach the surface. In the Self Potential Method (SPM), the distribution of natural electrical potential on the surface is measured and used to obtain information about what lies underground. In contrast, in the Induced Polarization Method (IPM), a one-way direct current is sent through a land mass to induce a polarized state in a latent underground structure, which is observed to obtain a profile of the geological structure.

1.2 Electrical potential method

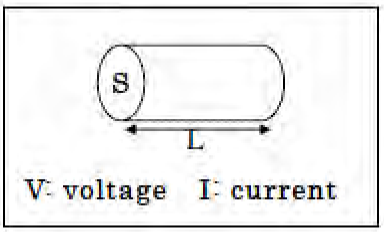
An artificial current is run through anodes in a large land mass to measure the distribution of the magnetic field on the ground surface. This is used to derive the apparent resistsivity distribution and/or the deviation of the electrical potential and profile the underground structure.

1.3 Resistivity method

The difference in electrical potential between two points on the ground surface is directly measured to calculate the apparent resistivity. The result then provides the basis for analyzing the structure of relative resistivity below the ground. Because the relative resistivity method can be used to effectively survey underground structure using various combinations of electrode intervals (spacings), it is the most widely used method for electrical prospecting.

This manual was created as a handbook for conducting groundwater surveys using the relative resistivity method. In the case of outdoor surveys, there is a fixed procedure, starting with proposal of preliminary survey plans, setting up measuring points, measurement preparations, measurements, analyses, selection of points for well-drilling, and giving instructions to the drilling team.

2 Resistivity method



Assuming the electrical current I(A) that runs when the voltage V that is sent to an object is V, then the electrical resistance R of an object can be expressed as R=V/I, which is here referred to as Ohm's Law. Ordinarily, electrical resistance depends on the shape of the object. For a cylindrical object having a longitudinal area of Sm^2 and length of Lm, R is expressed as being equal to $\rho L/S$, with ρ representing the relative resistance. In this case, the unit is ohm-m.

Wenner proposed a method for installing an electrode in the ground to measure the relative resistance of a land mass. As we can see in Figure 2, there is an arrangement of 4 electrodes: C_1 and C_2 installed at 2 locations, and P_1 and P_2. The electrical potential ϕ_1 can be expressed as

$$\phi_1 = \rho I/2\pi\ (1/C_1P_1 - 1/C_2P_1)$$

Adding electrical potential ϕ_2 in P_2 ultimately gives us the difference in electrical potential, V, between P_1 and P_2

$$V = \phi_1 - \phi_2 = \rho I/2\pi\,(1/C_1P_1 + 1/C_2P_2 - 1/C_2P_1 - 1/C_1P_2)$$

When $r_1 = r_4 = a$, $r_2 = r_3 = 2a$ in Figure 2, that is, the CPPC configuration is used for the equal spacing of the 4 electrodes (see Wenner, Table 1), then the difference in electrical potential is expressed as

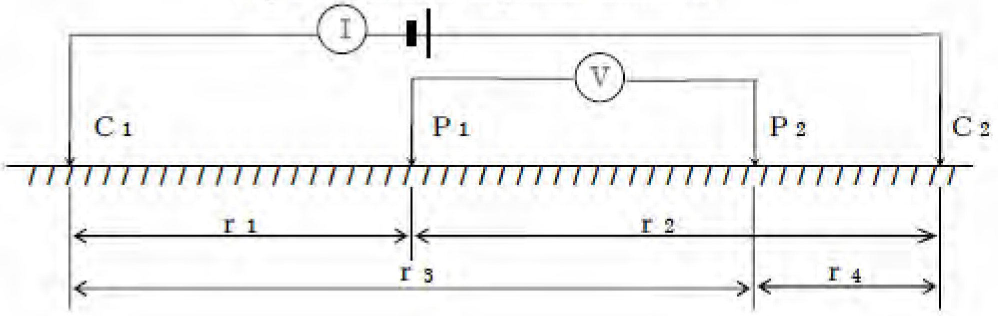
$$V = \rho I/2\pi a$$

from this equation, we can derive

$$\rho = 2\pi a(V/I)$$

which is known as the Wenner formula. It is ordinarily expressed as $\rho = G(V/I)$, where G is the electrode arrangement coefficient.

Fig.2 Electrode arrangement coefficient

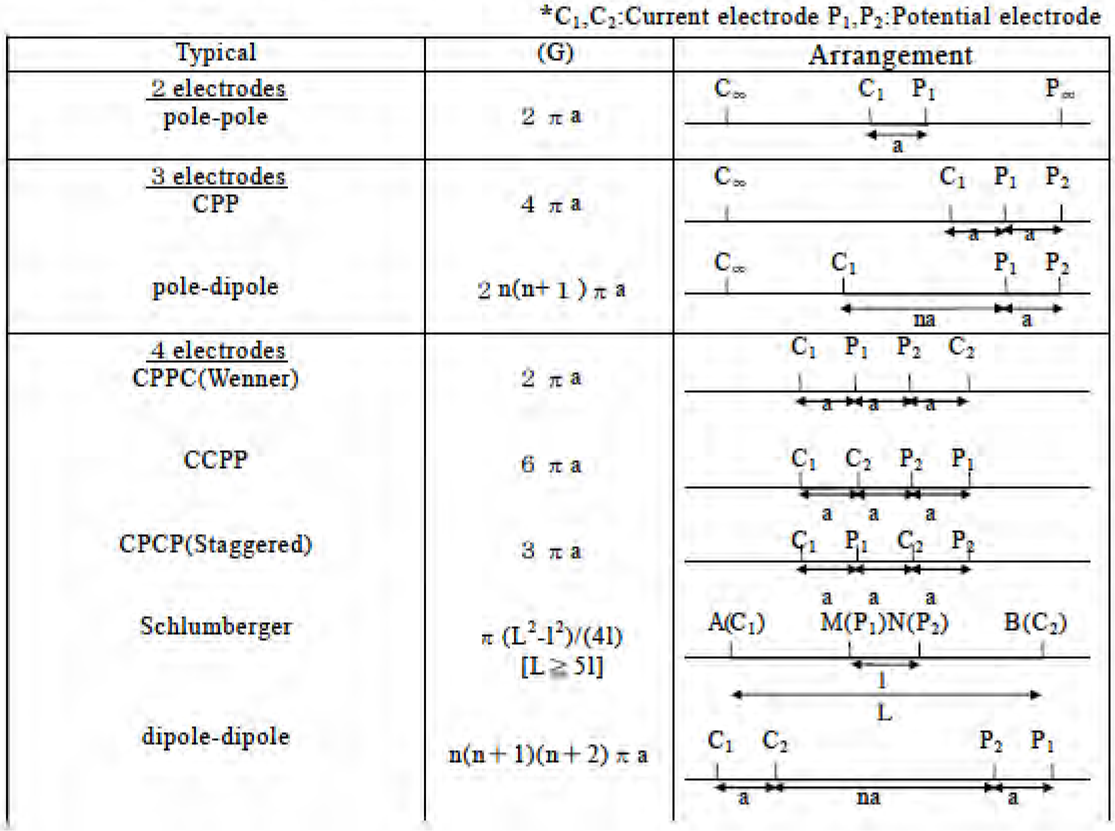


This relative equation shows the relative resistivity of a homogenous medium; however, since land is not homogenous, the value derived from the equation will not represent the true relative resistivity of the land. However, the value will be affected by all the substances which make up the underground medium and will be a physical volume having some sort of functional relation with the relative resistivity of these substances. Therefore, the value derived from this equation is differentiated from true relative resistivity by calling it apparent resistivity ρ a, which is defined as ρ a=G(V/I).

The value of this ρ a is dependent on such things as the electrode spacing, location of the electrode system, and directionality of the electrode arrangement, so if the equation ρ a=G(V/I) is applied to many different observation conditions, we can estimate the relative resistivity structure of the subsurface.

The following table shows typical polarity arrangements and associated polarity arrangement coefficient. In addition, Table 2 (Relative resistivity of rock) and Figure 3 (Relative resistivity of rock, groundwater, etc.) show general relations between geology and relative resistivity.

Table1 Typical polarity arrangements and polarity arrangement coefficients



*C_1,C_2:Current electrode P_1,P_2:Potential electrode

Typical	(G)	Arrangement
2 electrodes pole-pole	$2\pi a$	C_∞ C_1 P_1 P_∞ a
3 electrodes CPP	$4\pi a$	C_∞ C_1 P_1 P_2 a a
pole-dipole	$2n(n+1)\pi a$	C_∞ C_1 P_1 P_2 na a
4 electrodes CPPC(Wenner)	$2\pi a$	C_1 P_1 P_2 C_2 a a a
CCPP	$6\pi a$	C_1 C_2 P_2 P_1 a a a
CPCP(Staggered)	$3\pi a$	C_1 P_1 C_2 P_2 a a a
Schlumberger	$\pi(L^2-l^2)/(4l)$ $[L \geq 5l]$	A(C_1) M(P_1)N(P_2) B(C_2) l L
dipole-dipole	$n(n+1)(n+2)\pi a$	C_1 C_2 P_2 P_1 a na a

Table2 Resistivity range of rocks unit:ohm-m

Geologic age	Marine sand, shale, graywacke	Terrestrial sands, claystone, arkose	Volcanic rocks (basalt,rhyolite, tuffs)	Granite, gabboro, Etc.	Limestone, dolomite, anhydrite,salt
Quaternary,Tertiary	1-10	15-50	10-200	500-2000	50-5000
Mesozoic	5-20	25-100	20-500	500-2000	100-10000
Carboniferous	10-40	50-300	50-1000	1000-5000	200-100000
Pre-Carboniferous Paleozoic	40-200	100-500	100-2000	1000-5000	10000-100000
Precambrian	100-2200	300-5000	200-5000	5000-20000	10000-100000

*source: G.R.Keller Handbook of Physical Constant

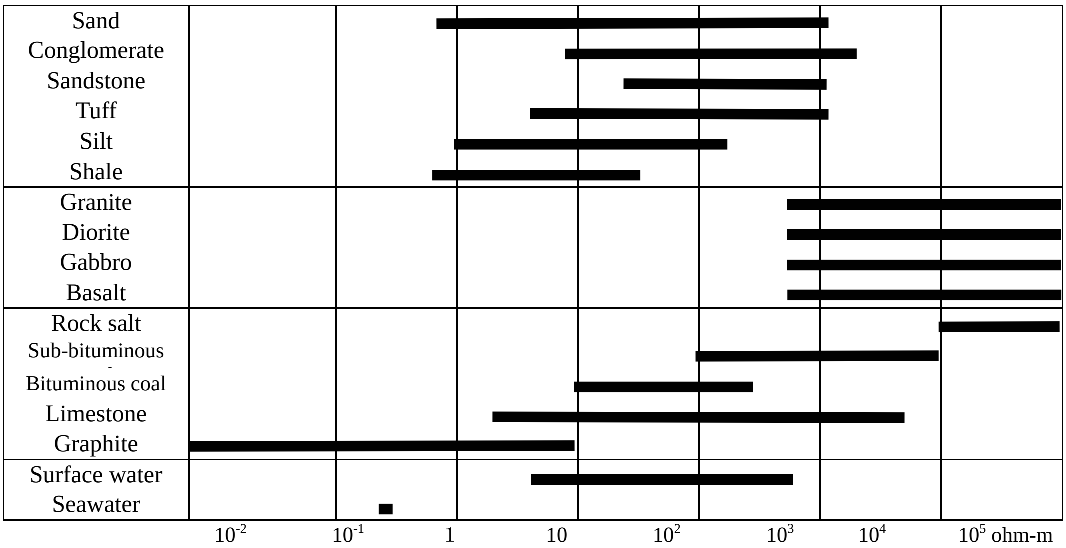


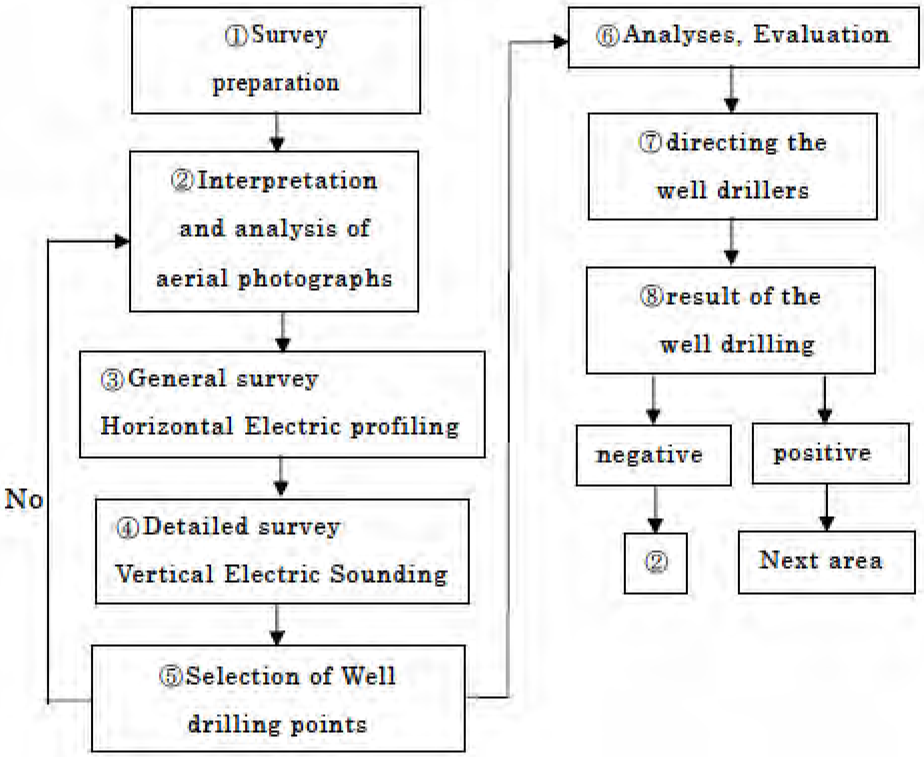
Fig.3 Relative resistivity of rock, groundwater, etc.
(Source: Society of Exploration Geophysicists of Japan, 1989)

>From Figure 3, we can see that there are differences in relative resistivity values, even within the same type of rock, while in other cases, different types of rock show roughly the same values. Thus, it is difficult to determine the type of rock just from relative resistivity values. This is because the pressure, metamorphism, decomposition, heat, groundwater permeation, etc., can all vary, and there can be differences in pore spacing, relative resistivity of pore water, water content, and concentration of ions in the groundwater, among other variables.

3 Survey flow chart

Electrical survey is a mainly 6-stage process comprising 1) survey preparation, 2) establishing baselines through interpretation and analysis of aerial photographs, 3) general survey involving Horizontal Electric Profiling, 4) detailed survey involving conducting Vertical Electric Sounding, 5) analysis of electric profile measurement data and selection of sites for well drilling, and 6) providing instructions to the well drillers. The flow chart is shown next page:

Fig.4 Survey flow chart



① Survey preparation

Before starting the in site survey, materials and information (e.g., geologic maps, aerial photographs, existing well data, hydro geological data, etc.) are collected from each region and community. Then the target communities and number of wells requested are reconfirmed with an organization of the partner country (C/P local office), negotiations are made to acquire land for the planned electrical prospecting sites, and various aspects of the project are checked, including agreement of local residents to the well project, locations of communities, land use conditions, and road conditions. It is especially important at well-drilling sites to secure road access and land so that drilling rigs and other work vehicles can enter the site without hindrance.

② Interpretation and analysis of aerial photographs

Aerial photographs are interpreted and analyzed to identify lineaments that strongly suggest the existence of groundwater, and determine the locations and directions of baselines. Analysis is conducted before the photographs are analyzed. In addition, detailed analyses are made at prospective well sites that local residents prefer.

③ General survey (Horizontal Electric Profiling)

The purpose of the general survey is to identify abnormal values of apparent resistivity (zones of crushed rock in the foundation rock and/or points that differ from the surrounding geological structure) and select Horizontal Electric Profiling points to determine the site of drilling.

Wenner's formula is used for the horizontal profiling. Maintaining a constant polarity distance a in the polarity arrangement in Fig. 5, Wenner's formula is used to measure apparent resistivity while moving along the baseline of the entire polarity system. The profiling is done at a constant depth that is roughly equal to polarity distance a to investigate the apparent resistivity of horizontal changes. The following is an overview of the measuring equipment specifications and the contents of the survey.

Measuring method: Wenner Method

Measuring equipment: Syscal-R2 and DC-DC converter (BRGM, France)……as an example

Syscal-R2 is a compact integrated unit for sending and receiving signals. It is operated with a keyboard and LCD dialogue-type displays on the screen. An internal electrode configuration, geometric parameters, etc., are selected and the measurements are taken. In addition, values required for the measuring conditions, such as electrical current, electrical displacement, number of staking are set automatically, and the apparent relative resistance is calculated from the measured values. The DC-DC converter supplies high voltage power from the external power source on the transmitter.

Baseline length: 1 baseline is about 100～300m in length, which can be extended depending on the results of the profiling.

Polarity distance (spacing): There are several types from a=20～80m (Polarity spacing is determined by the geological conditions; in this example, a=30m、60m、80m).

Equipment used in the measurements: 12V battery, electrodes (iron or stainless steel rods about 50cm long and 2cm in diameter), electrical wire (voltage resistance of 1kV or more), 1.5mm^2 or more of covered copper wire, measuring tape (100m), 5 hammers, pliers, electrical tape, etc.

Measuring time: 1-2 hours per baseline

Number of workers: 4-5

Measuring method

The procedure for measuring with the Wenner method is as follows:

i) At the prospective well site, determine the direction in which the baseline is to be developed. However, it should be noted that there are very poor lineaments in some areas, so in these areas the baseline should be perpendicular to the geological structure of the crushed zone, etc., or to the strike. However, if even these are not clear, the baseline location can even be set in a random direction near the prospective well site.

ii) Using simple measuring equipment, the baseline direction determines the locations of measuring points (electrodes) at equal intervals of lateral distance. The baseline should be as straight as possible. Sometimes it is necessary to remove vegetation.

iii) With the measuring point as the central point, electrodes A and B for measuring current should be set up on the outside, while electrodes M and N for measuring electrical displacement should be set up on the inside (nearest the measuring point). Electrodes and measuring points should be in a straight line. Then each electrode rod should be hammered into the ground (see Fig. 5). The resistivity of the ground the rods touch should not exceed a few hundred ohms.

In dry zones or thin surface soil regions, the area around an electrode can become dry while the current is running and disrupt the transmission of the electrical signal. In such cases, the ground should be watered to establish good contact between electrode and ground, or the number of electrodes can be increased to reduce the contact resistivity of the ground around the electrode.

iv) An electrical wire is attached to each electrode rod, and the other end of the wire is connected to measuring equipment. New wire should be used to prevent current leakage.

v) Connect the 12V battery to the measuring device, set the maximum transmission current to within 500mA or so, run the current through the electrodes and measure electrical displacement.

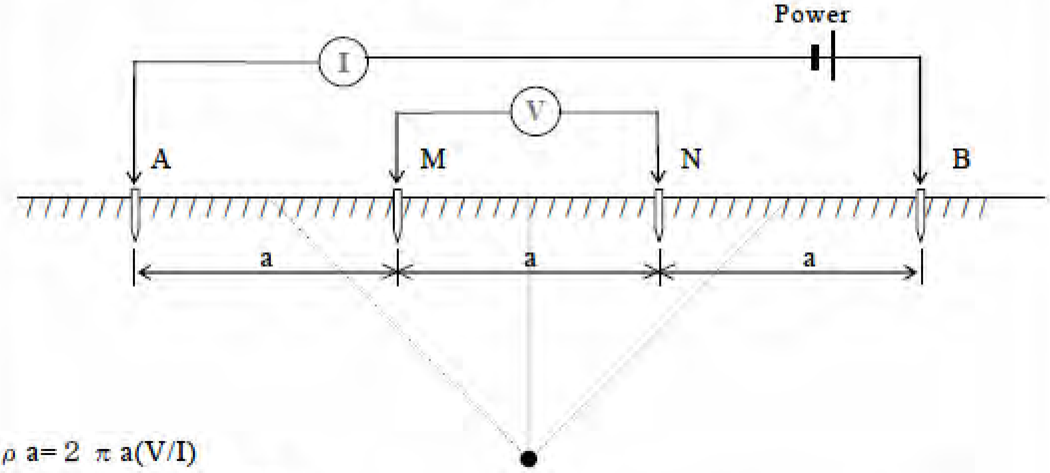
vi) Enter the measurement data in the field book, and plot it as the apparent relative resistance curve (apparent relative resistance (ρ a)—electrode interval(a)) on logarithmic graph paper (see Fig. 6)

vii) After finishing measurements at one point, go to the next point and repeat the above procedure in the prescribed order (see Fig. 7). The measurement distance should be intervals of about 10m on the baseline. If the measurement interval exceeds 10m, there is a chance that points with a distinguishing geological structure may not be detected.

viii) After all measurements at an electrode spacing of a =30m have been completed, change the spacing to a =60m then a =80m, and take measurements along the same baseline but in the opposite direction as before.

ix) After completing all the measurements (electrode spacing of a =30m、a =60m and a =80m) along the same baseline, identify the abnormal points in the plotted graphs, and use them for the measuring points for the Vertical Electric Sounding in the detailed survey. Mark the abnormal points with a wooden stake and cover it with rocks, etc., to make it noticeable and to protect it. If no abnormalities are detected, set up a new baseline and take more measurements.

Fig.5 Wenner Method



ρ a= 2 π a(V/I)

a: electrode spacing

V: potential between of M and N(V), I: current between of A and B(A)

AB: current electrode, MN: potential electrode,

ρ a=apparent resistivity(ohm-m)

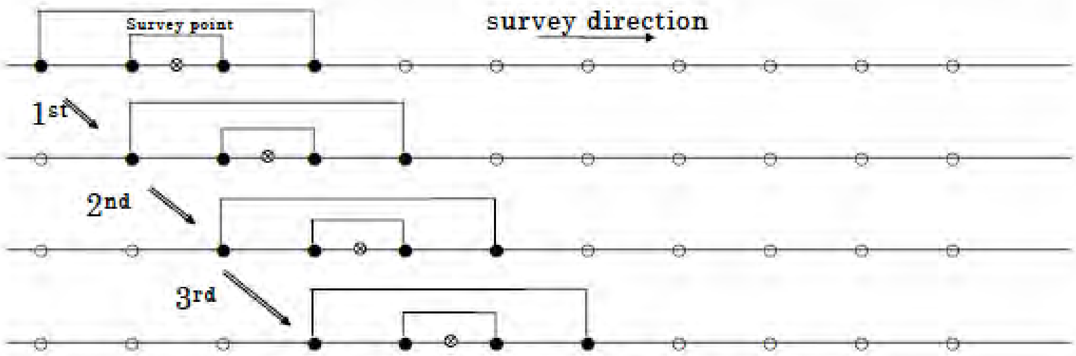


Fig. 7 Methodology of the Wenner method

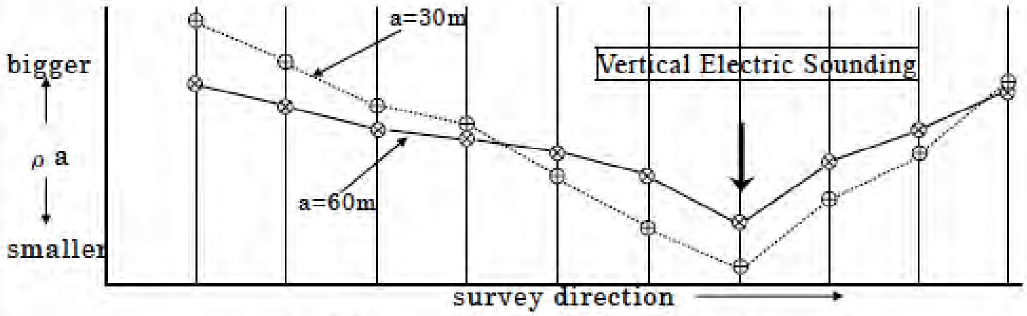


Fig.6 Apparent resisivity profiling(ρ a－a)

④ Detailed survey (Vertical Electric Sounding)

The Schlumberger Method is a way of probing the underground structure of a level layer. The center of the symmetrically-arranged electrode system is fixed in place, while the current, electrical potential and polarity intervals are varied to measure apparent resistivity ρa. The ρa- a curve derived therefrom is used to obtain the thicknesses of the level layers and their relative resistivity. In other words, current is transmitted through outer electrodes A and B that are installed on the measurement line, while electrodes M and N on the inside are used to measure differences in electrical potential (see Figure 8). The equipment used for these measurements is the same equipment used in the horizontal electric profiling.

Name of method: Schlumberger Method

Exploration depth: (AB/2): 1-500m (maximum)

Measuring time: 40-90 minutes/point

Number of workers: 4-5

Measuring method

The probe points are points with abnormalities that were identified by the horizontal electric profiling. There should be at least 2 probe points for each prospective well.

i) With the abnormal point as the central point, the development direction of both sides of the baseline is determined.

ii) The baseline should be as straight as possible.

iii) An electrode rod is inserted into the ground at the central point and the measuring equipment is set up. Table 3 and Figure 9 show examples of combinations of the current-electrode interval (AB/2) and the electrical potential-electrode interval (MN/2). Electrode sticks are inserted into the ground at points A, M, N and B shown in the table.

iv)The ground/earth resistivity should not exceed 100 ohms.

v)An electrical wire is connected to each electrode stick, and the other end of the wire is connected to the measuring equipment.

vi)Measurements are commenced with a maximum transmission current of 500mA. The wider the spacing between electrodes becomes, the lower the S/N (signal/noise) ratio becomes, with the result the standard deviation of the secondary electrical potential will increase, making it difficult to reproduce the data.

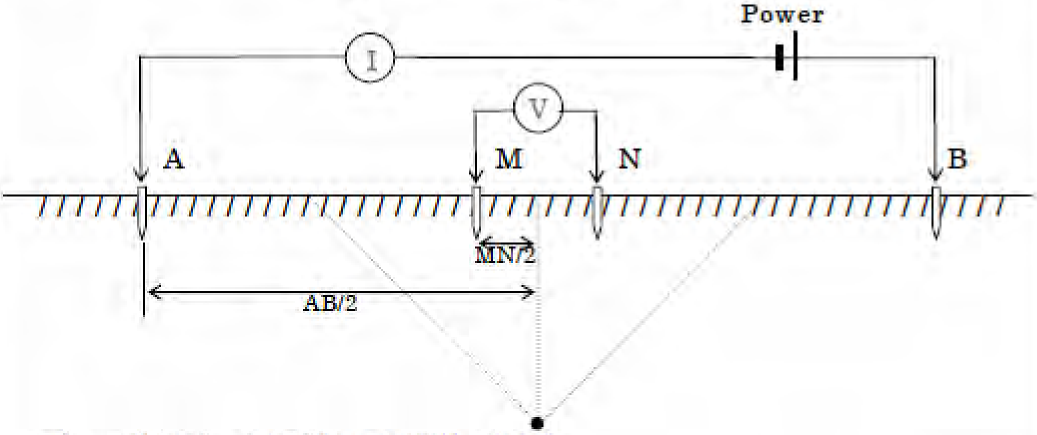
vii)The measurement data are recorded in a log book and plotted on the ρa－a apparent resistivity curve on double-logarithm graph paper.

viii)When the electrical potential and electrode intervals are varied, repetitive measurements are taken at two types of current-polarity intervals.

ix)When measurements have been taken using all combinations of polarity intervals, move on to the next point and repeat the measurement procedure.

After the probing has ended, determine whether or not groundwater may exist based on the plots that were made of several locations. If the possibility is low, look for another probe site and conduct another horizontal electric profiling for resistivity, and choose a new site for the detailed survey.

Fig.8 Schlumberger Method



$\rho a=\{\pi \times((AB^2-MN^2)/4\times MN)\}\times(V/I)$

V:potential between of M and N(V), I: current between of A and B(A)

AB: current electrode, MN: potential electrode, ρ a=apparent resistivity(ohm-m)

Table3 Schlumberger combinations of AB/2 and MN/2.

(AB/2)	1	2	4	6	8	10	15	20	25
(MN/2)	0. 2	0. 2	0. 2	0. 2/1	0. 2/1	1	1	1	1/5
(AB/2)	30	35	40	45	50	60	70	80	90
(MN/2)	1/5	5	5	5	5/10	5/10	10	10	10
(AB/2)	100	120	140	170	200	250	300	400	500
(MN/2)	10/20	10/20	20	20	20/50	50	50	50	50

*AB/2(m):current-electrode interval, MN/2(m):electrical potential-electrode interval,
AB ≧5×MN

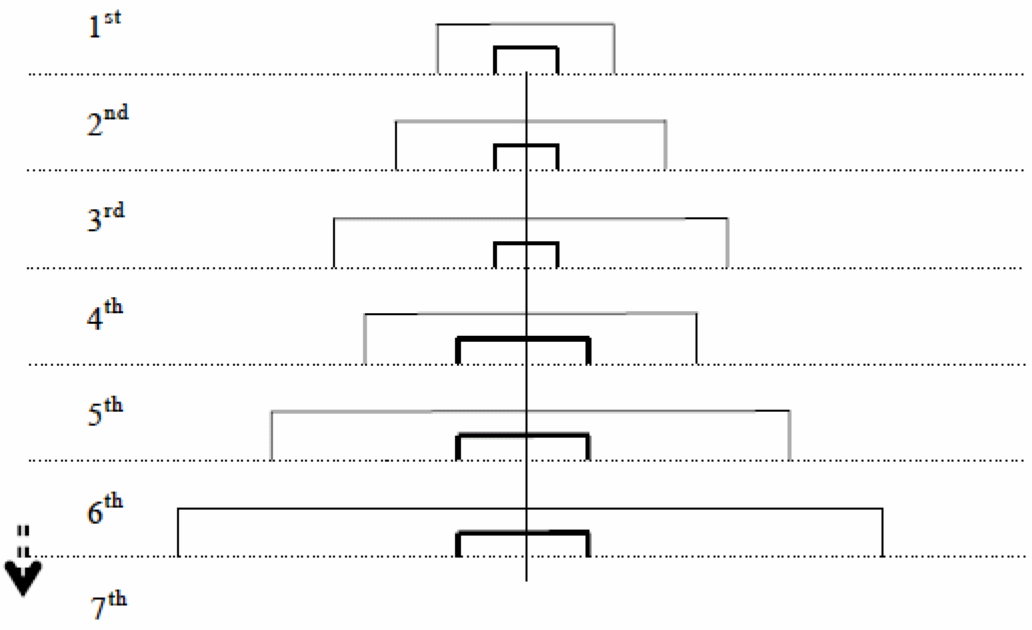


Fig. 9 Measurement method based on Schlumberger's arrangement of electrodes

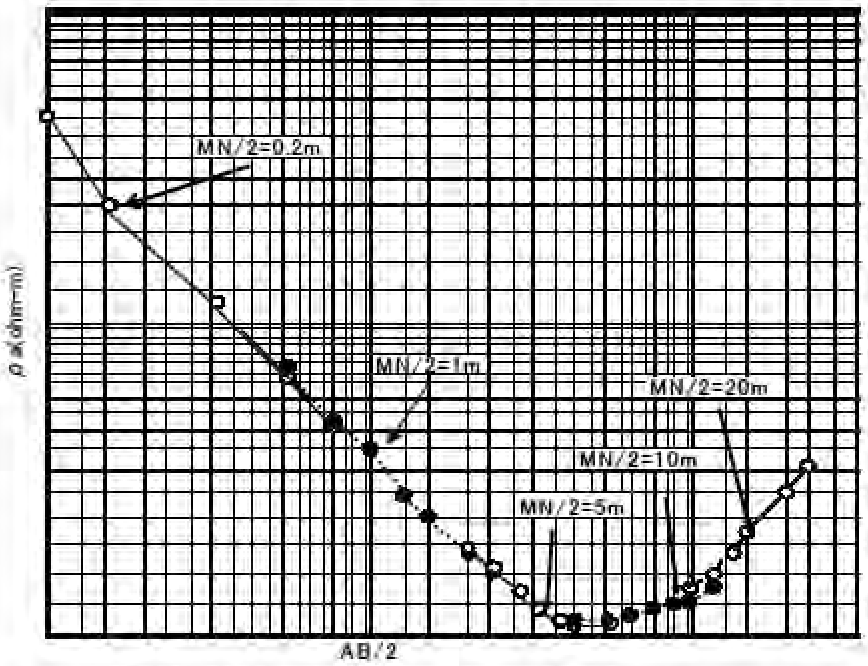


Fig10 ρa − a apparent relative tesistance curve

⑤ Analyses, selection of well drilling points, and instructions for the drilling crew

Analyses are conducted at all measuring points based on the Vertical Electric Sounding data (see Fig. 11).

Electrical probe analysis software is used on a PC to make one-dimensional analyses. The results are estimated relative resistivity which assume a horizontal layer structure. The relative resistivity model is used to conduct analyses by considering the groundwater level and excavation depth of existing wells, the analytical results from neighboring points, topography, geology, and so on. Drilling candidate sites are selected based on their potential for groundwater (in order from highest to lowest), meetings are held to deliberate on candidate sites C/P local office, and villagers' desired sites are also considered when establishing the order of preference.

The locations and GPS coordinates of candidate sites are clearly marked on a location map. Detailed maps of measuring points and lines are made using simple measuring equipment and referring to reference points which might include an unusual landform or manmade object(s) within the survey area. An analytical results diagram is juxtaposed on the map containing this information and used for giving instructions to the drilling crew. The results of the well drilling are conveyed to the electrical probe team as feedback and compared with the drilling results, and used as reference data for subsequent investigations and analyses.

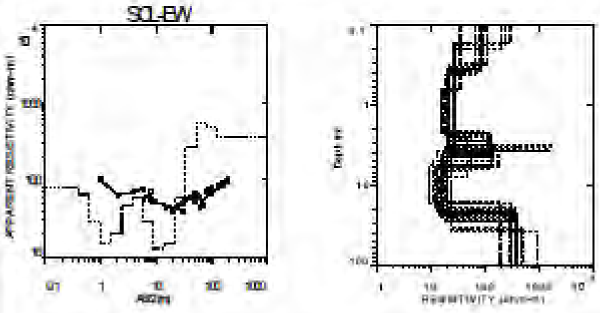


Fig.11 Result of the sounding interpretation

4 Important points about measurements

Points requiring special attention when conducting electrical prospecting.

i) Artificial noise

In many instances, structures that are not related to the local geology generate abnormalities, so these structures must be avoided as much as possible. For example, steel-reinforced buildings, buried steel pipes, metal fences, industrial waste dumps that contain conductive materials, heavily traveled roads and railways, high transmission electric power lines, grounding cables for telephone/telegraph poles, etc., can hamper electric potential measurements.

ii) Natural noise

When lightning strikes a power line, it can cause a power surge that can damage electrical equipment, and users can even be electrically shocked. If thunder is heard, the equipment should be removed and workers evacuated to a safe place.

iii) Topography

It is extremely difficult to work on steep slopes, such as those exceeding 45 degrees.

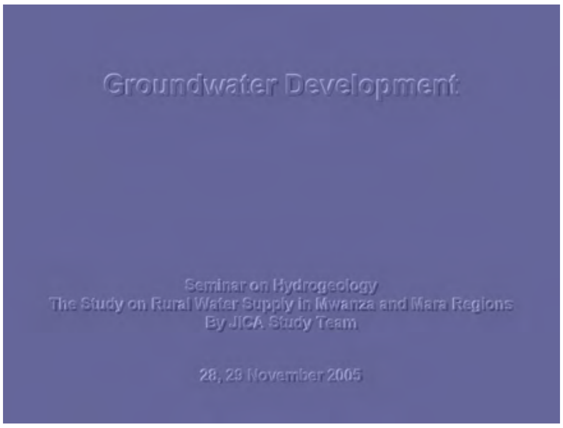
5 Arranging the survey results

The following should be considered for the results of electrical exploration.

- Survey location maps, measuring point maps, survey data tables, and apparent resistivity diagrams made from Horizontal Electric Profiling.
- Correlation diagrams of analyzed resistivity diagrams, interpreted section for vertical electric sounding, analytical results (estimated excavated depth tables), geological maps and probe results (observations of obtained results).
- Comparison of survey results with boring data.
- Comparison of results of present and previous surveys.
- Comparisons between survey results and geology
- Other

② Hydrogeology

SLIDES FOR GROUNDWATER DEVELOPMENT WORKSHOP


Groundwater Development

Seminar on Hydrogeology
The Study on Rural Water Supply in Mwanza and Mara Regions
By JICA Study Team

28, 29 November 2005


CONTENTS OF THE SEMINAR

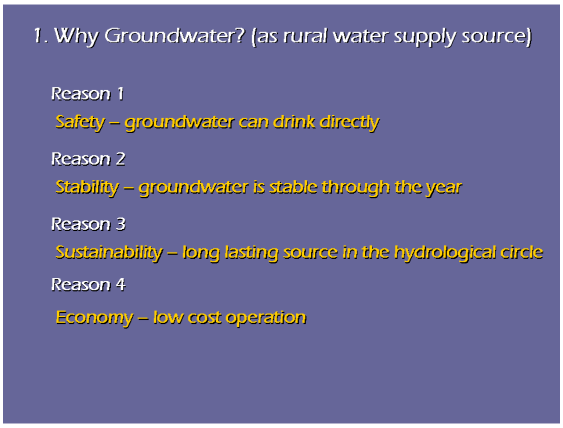
PART I OUTLINE OF GROUNDWATER DEVELOPMENT
PART II GROUNDWATER AVAILABILITY MAP
PART III INTERPRETATION OF AERIAL PHOTOGRAPH

OBJECTIVE OF THE SEMINAR

TO UNDERSTAND THE GROUNDWATER DEVELOPMENT
TO EXCERSIZE THE METHOD OF INTERPRETATION
TO RECOGNIZE THE IMPORTANT INFORMATION


PART I OUTLINE OF GROUNDWATER DEVELOPMENT

1. Why Groundwater?
2. Process of Groundwater Development
3. Analysis of Development Potential
4. Risk of Groundwater Development

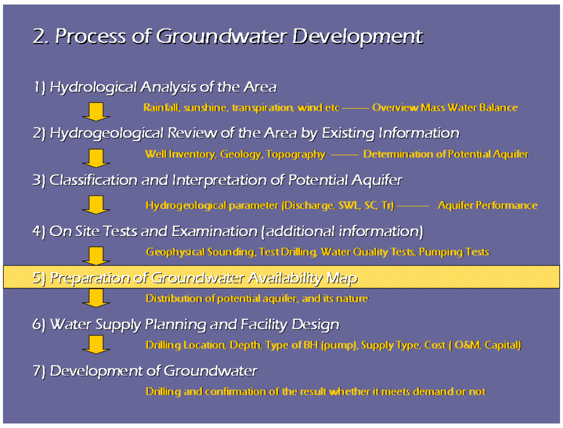

1. Why Groundwater? (as rural water supply source)

Reason 1
Safety – groundwater can drink directly

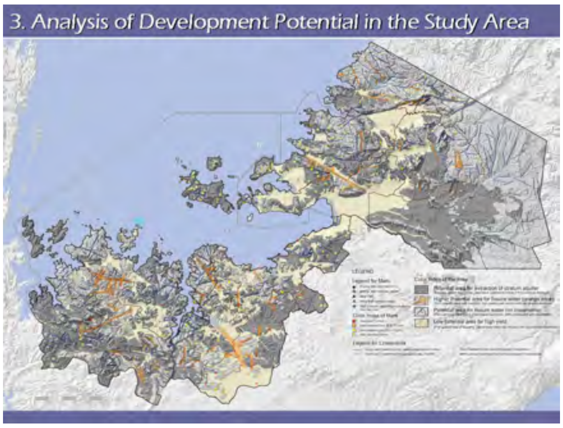
Reason 2
Stability – groundwater is stable through the year

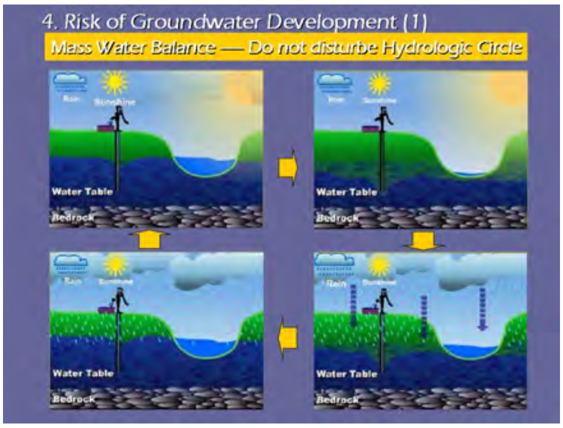
Reason 3
Sustainability – long lasting source in the hydrological circle

Reason 4
Economy – low cost operation


2. Process of Groundwater Development

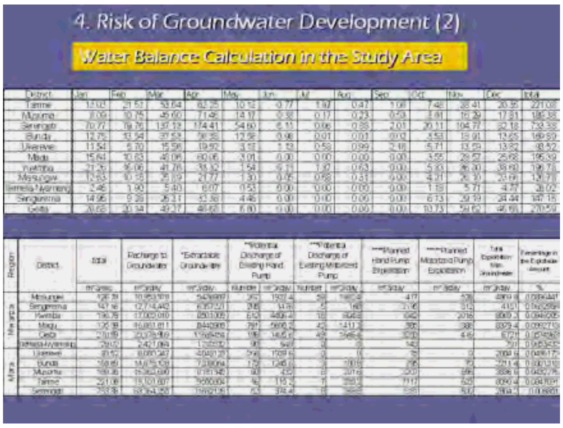
1) Hydrological Analysis of the Area
Rainfall, sunshine, transpiration, wind etc —— Overview Mass Water Balance
2) Hydrogeological Review of the Area by Existing Information
Well Inventory, Geology, Topography —— Determination of Potential Aquifer
3) Classification and Interpretation of Potential Aquifer
Hydrogeological parameter (Discharge, SWL, SC, Tr) —— Aquifer Performance
4) On Site Tests and Examination (additional information)
Geophysical Sounding, Test Drilling, Water Quality Tests, Pumping Tests
5) Preparation of Groundwater Availability Map
Distribution of potential aquifer, and its nature
6) Water Supply Planning and Facility Design
Drilling Location, Depth, Type of BH (pump), Supply Type, Cost (O&M, Capital)
7) Development of Groundwater
Drilling and confirmation of the result whether it meets demand or not


3. Analysis of Development Potential in the Study Area



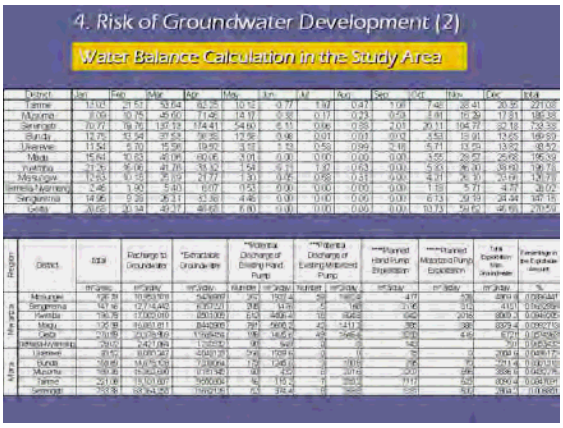
4. Risk of Groundwater Development (1)

Mass Water Balance — Do not disturb Hydrologic Circle



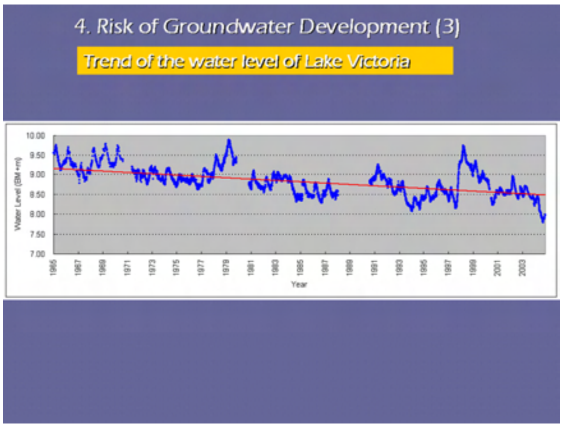
4. Risk of Groundwater Development (2)

Water Balance Calculation in the Study Area



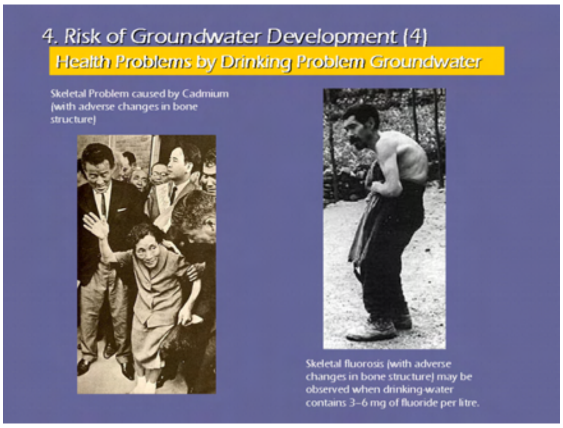
4. Risk of Groundwater Development (2)

Water Balance Calculation in the Study Area



4. Risk of Groundwater Development (3)

Trend of the water level of Lake Victoria

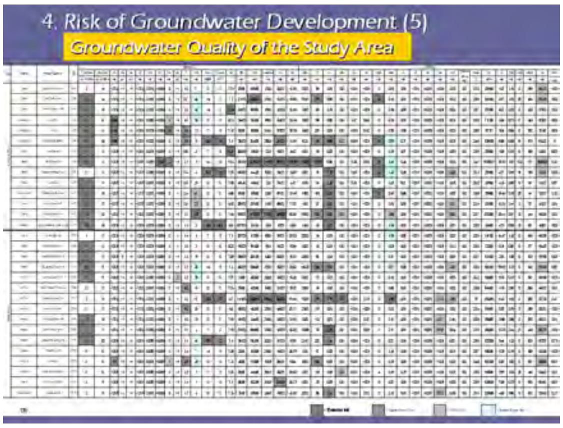


4. Risk of Groundwater Development (4)

Health Problems by Drinking Problem Groundwater

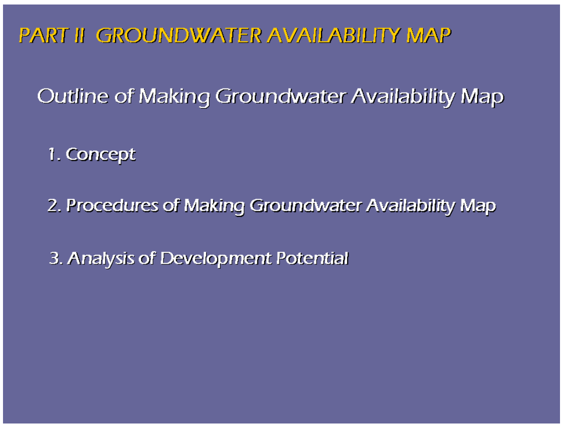
Skeletal Problem caused by Cadmium (with adverse changes in bone structure)

Skeletal fluorosis (with adverse changes in bone structure) may be observed when drinking-water contains 3–6 mg of fluoride per litre.



4. Risk of Groundwater Development (5)

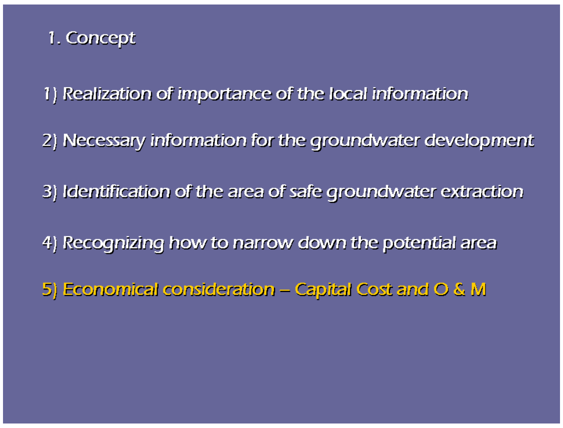
Groundwater Quality of the Study Area



PART II GROUNDWATER AVAILABILITY MAP

Outline of Making Groundwater Availability Map

1. Concept
2. Procedures of Making Groundwater Availability Map
3. Analysis of Development Potential



1. Concept

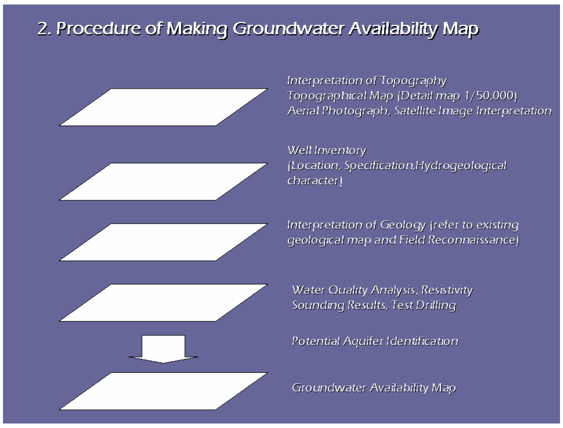
1) Realization of importance of the local information

2) Necessary information for the groundwater development

3) Identification of the area of safe groundwater extraction

4) Recognizing how to narrow down the potential area

5) Economical consideration – Capital Cost and O & M



2. Procedure of Making Groundwater Availability Map

Interpretation of Topography
Topographical Map (Detail map 1/50,000)
Aerial Photograph, Satellite Image Interpretation

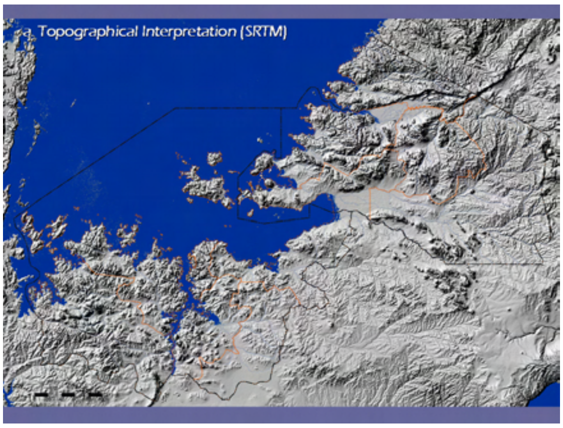
Well Inventory
(Location, Specification,Hydrogeological character)

Interpretation of Geology (refer to existing geological map and Field Reconnaissance)

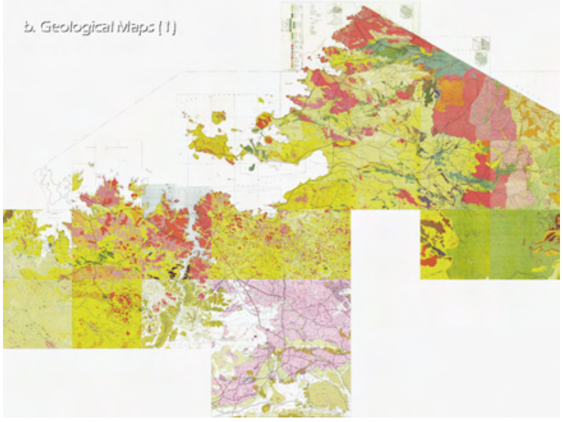
Water Quality Analysis, Resistivity Sounding Results, Test Drilling

Potential Aquifer Identification

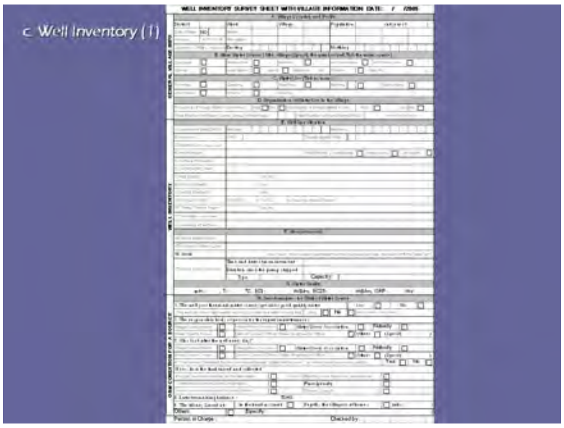
Groundwater Availability Map



a. Topographical Interpretation (SRTM)



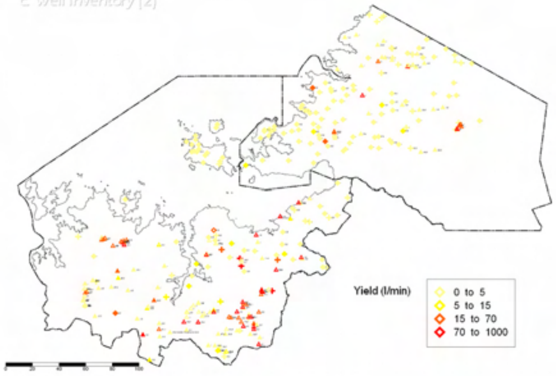
b. Geological Maps (1)



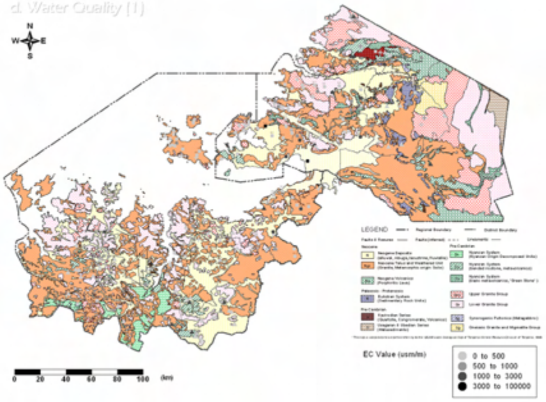
c. Well Inventory (1)

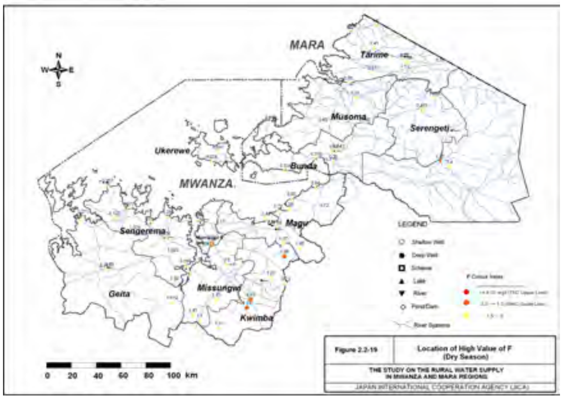
WELL INVENTORY SURVEY SHEET WITH VILLAGE INFORMATION DATE:

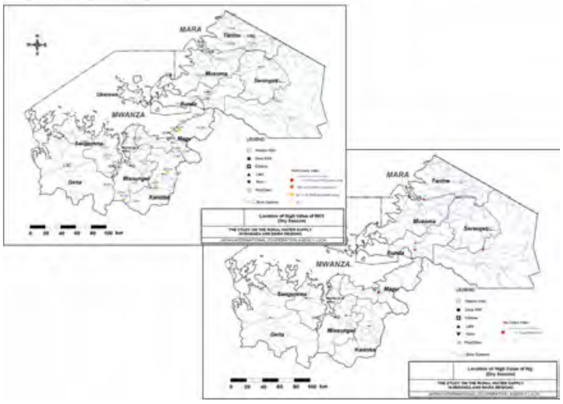
c. Well Inventory (2)

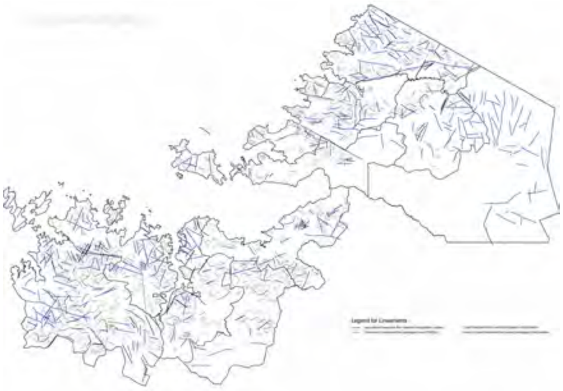


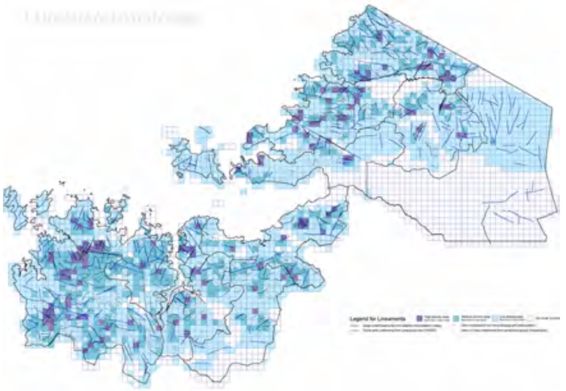
d. Water Quality (1)

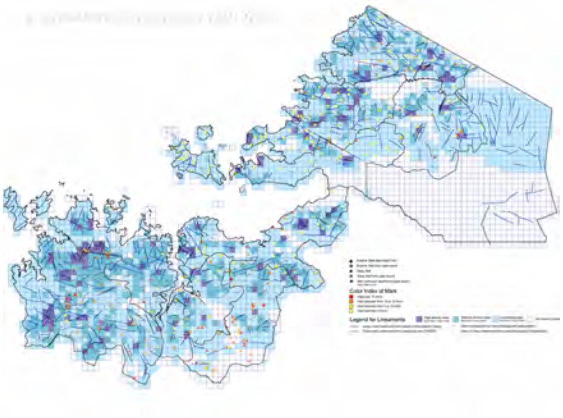


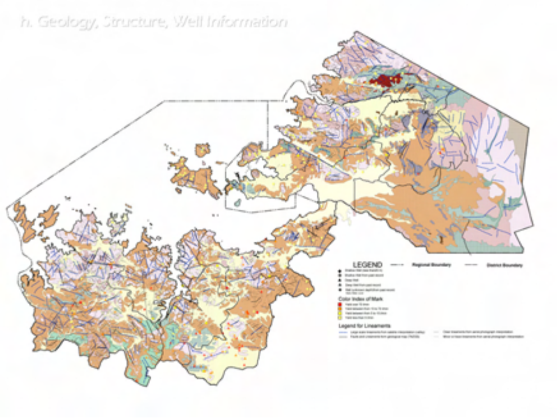


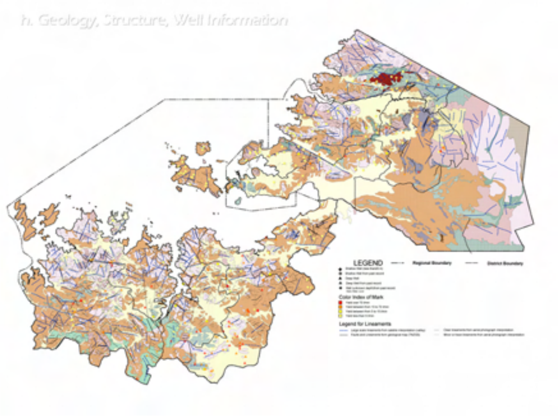


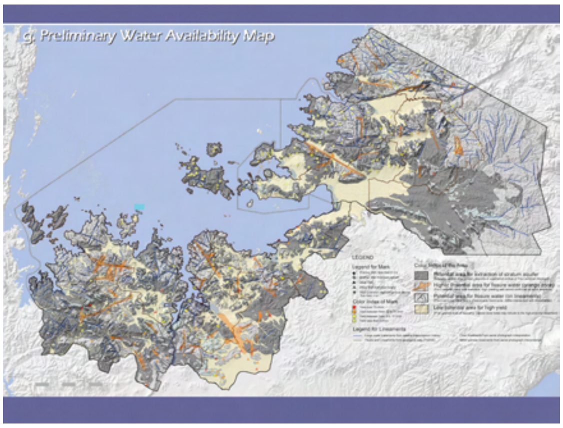


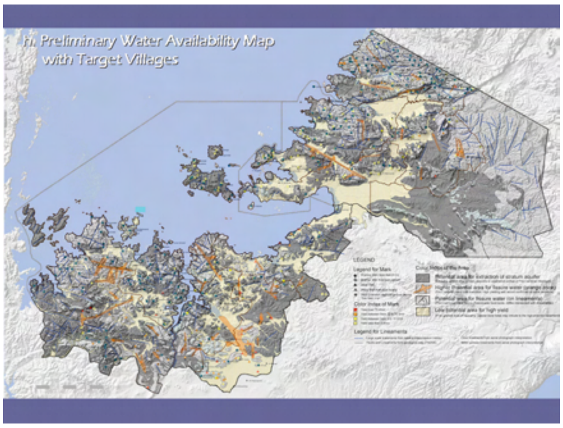


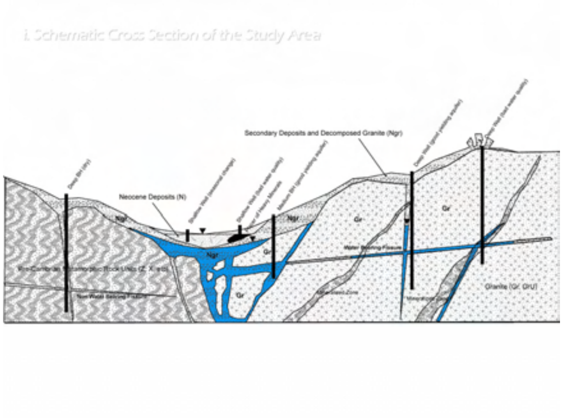


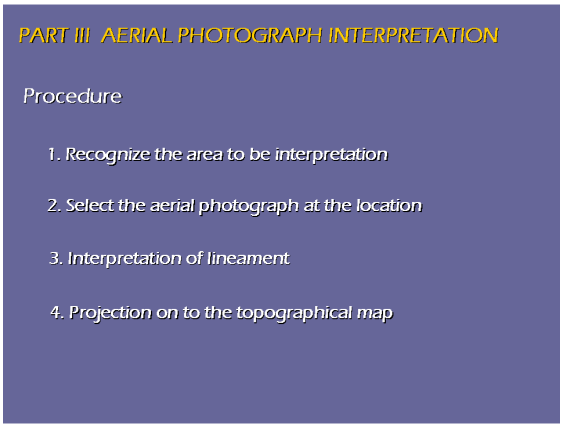

h. Geology, Structure, Well Information


h. Geology, Structure, Well Information


g. Preliminary Water Availability Map


h. Preliminary Water Availability Map
with Target Villages


i. Schematic Cross Section of the Study Area



PART III AERIAL PHOTOGRAPH INTERPRETATION

Procedure

1. Recognize the area to be interpretation
2. Select the aerial photograph at the location
3. Interpretation of lineament
4. Projection on to the topographical map

③ Test Well Drilling and Pumping Test

1 WATER WELLS

A water well is a hole or shaft, usually vertical, excavated in the earth for bringing groundwater to the surface. Occasionally wells serve other purposes, such as subsurface exploration and observation, artificial recharge, and disposal of wastewaters. Many methods exist for constructing wells; selection of a particular method depends on the purpose of the well, the quantity of water required, depth to groundwater, geologic conditions, and economic factors. Shallow wells are dug, bored, driven, or jetted; deep wells are drilled by cable tool or rotary methods. Attention to proper design will ensure efficient and long-lived wells. After a well has been drilled, it should be completed, developed for optimum yield, and tested. Wells should be sealed against entrance of surface pollution and given periodic maintenance. Wells of horizontal extent are constructed where warranted by special groundwater situations.

1.1 Methods for Drilling Deep Wells

Most large, deep, high-capacity wells are constructed by drilling. Construction can be accomplished by cable tool method or one of several rotary methods. Each method has particular advantages, so experienced drillers endeavor to have equipment available for a diversity of drilling approaches. Applications of drilling methods are listed in Table 1.1-1, while Table 1.1-2 indicates the performance of the methods in various geologic formations.

a. Cable Tool Method

Wells drilled by the cable tool (also percussion or standard) method are constructed with a standard well-drilling rig, percussion tools, and a bailer. The method is cable of drilling holes of 8 to 60 cm in diameter through consolidated rock materials to depths of 600 m. In consolidated sand and gravel, especially quicksand, it is least effective because the loose material slumps and caves around bit. Drilling is accomplished by regular lifting and dropping of a string tools. On the lower end, a bit with a relatively sharp chisel edge breaks the rock by impact.

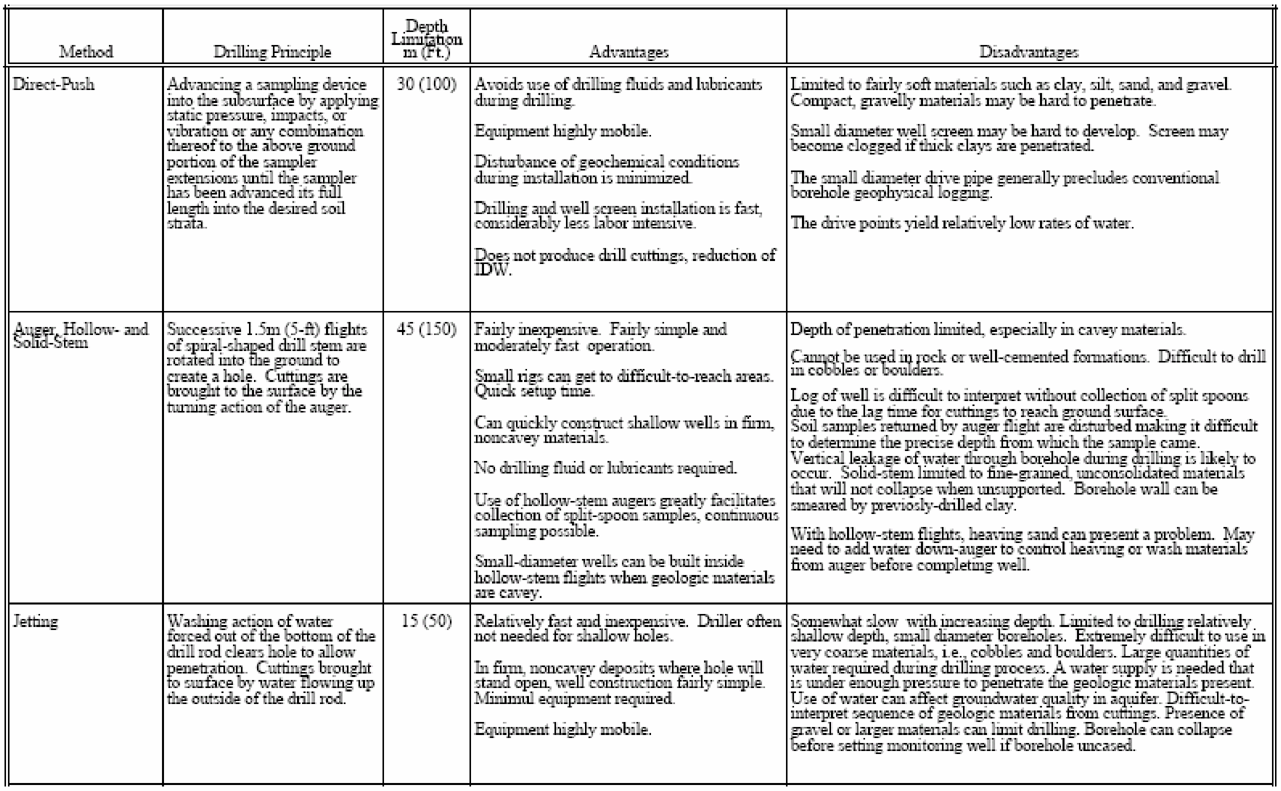
From top to bottom, a string of tools consists of swivel socket, a set of jars, a drill stem, and drilling bit (Figure 1.1-1). The total weight may amount to several thousand kilograms. Tools are made of steel and are jointed with tapered box-and-pin screw joints. The most important part of the string of tools is the bit, which does the actual drilling. Bits are manufactured in length of 1 to 3 m and weigh up to 1,500 kg. Various shaped bits are made for drilling in different rock formation.

Drilling cuttings are removed from the well by a bailer or sand bucket (Figure 1.1-1). Although several models are manufactured, a bailer consists essentially of section of pipe with a valve at the bottom and a ring at the top for attachment to the bailer line. Bailers are available in a range of diameters, lengths of 3 to 8 m, and capacities up to 0.25 m^3.

The drilling rig for the cable tool method consists of mast, multiline hoists, a walking beam, and an engine. In most present-day designs the entire assembly is truck-mounted (Figure 1.1-2) for ready portability.

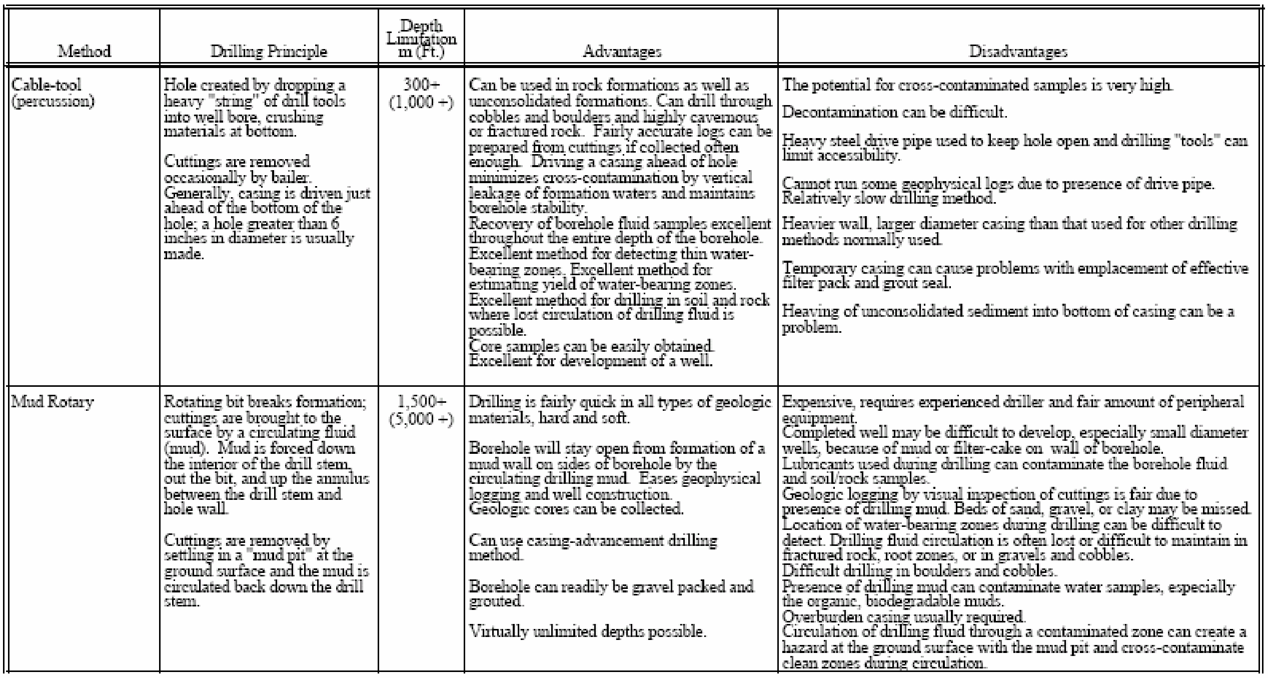
Table 1.1-1: Water Construction Methods and Application

(a)



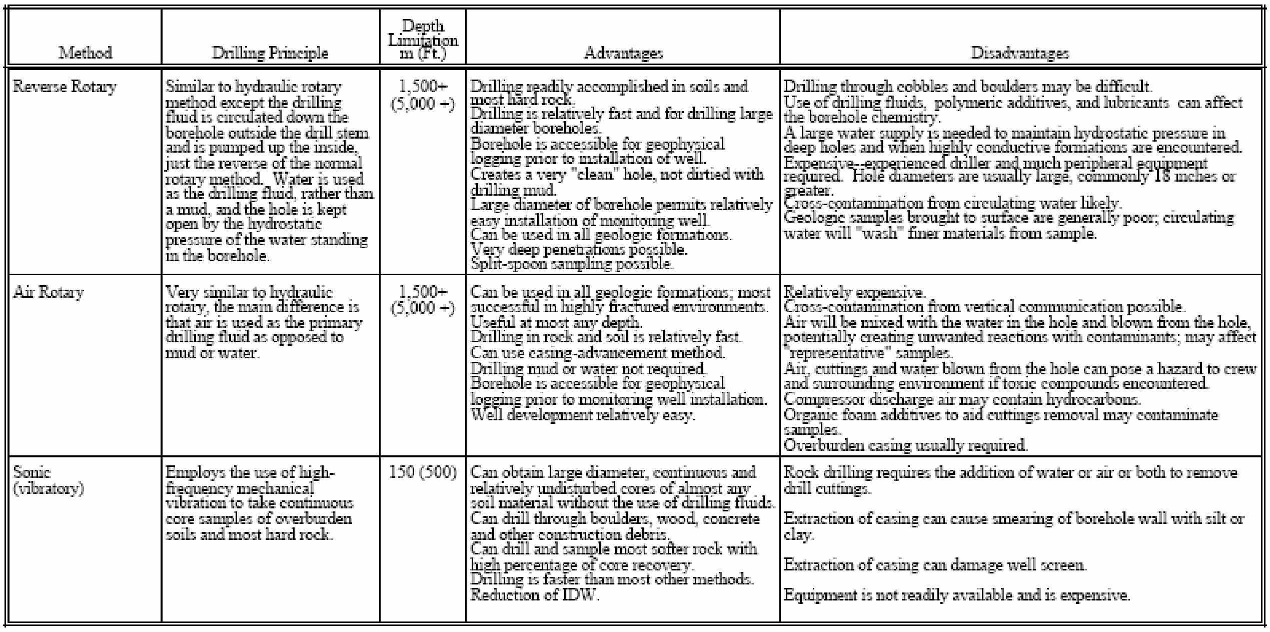
Method	Drilling Principle	Depth Limitation m (Ft.)	Advantages	Disadvantages
Direct-Push	Advancing a sampling device into the subsurface by applying static pressure, impacts, or vibration or any combination thereof to the above ground portion of the sampler extensions until the sampler has been advanced its full length into the desired soil strata.	30 (100)	Avoids use of drilling fluids and lubricants during drilling. Equipment highly mobile. Disturbance of geochemical conditions during installation is minimized. Drilling and well screen installation is fast, considerably less labor intensive. Does not produce drill cuttings, reduction of IDW.	Limited to fairly soft materials such as clay, silt, sand, and gravel. Compact, gravelly materials may be hard to penetrate. Small diameter well screen may be hard to develop. Screen may become clogged if thick clays are penetrated. The small diameter drive pipe generally precludes conventional borehole geophysical logging. The drive points yield relatively low rates of water.
Auger, Hollow- and Solid-Stem	Successive 1.5m (5-ft) flights of spiral-shaped drill stem are rotated into the ground to create a hole. Cuttings are brought to the surface by the turning action of the auger.	45 (150)	Fairly inexpensive. Fairly simple and moderately fast operation. Small rigs can get to difficult-to-reach areas. Quick setup time. Can quickly construct shallow wells in firm, noncavey materials. No drilling fluid or lubricants required. Use of hollow-stem augers greatly facilitates collection of split-spoon samples, continuous sampling possible. Small-diameter wells can be built inside hollow-stem flights when geologic materials are cavey.	Depth of penetration limited, especially in cavey materials. Cannot be used in rock or well-cemented formations. Difficult to drill in cobbles or boulders. Log of well is difficult to interpret without collection of split spoons due to the lag time for cuttings to reach ground surface. Soil samples returned by auger flight are disturbed making it difficult to determine the precise depth from which the sample came. Vertical leakage of water through borehole during drilling is likely to occur. Solid-stem limited to fine-grained, unconsolidated materials that will not collapse when unsupported. Borehole wall can be smeared by previosly-drilled clay. With hollow-stem flights, heaving sand can present a problem. May need to add water down-auger to control heaving or wash materials from auger before completing well.
Jetting	Washing action of water forced out of the bottom of the drill rod clears hole to allow penetration. Cuttings brought to surface by water flowing up the outside of the drill rod.	15 (50)	Relatively fast and inexpensive. Driller often not needed for shallow holes. In firm, noncavey deposits where hole will stand open, well construction fairly simple. Minimul equipment required. Equipment highly mobile.	Somewhat slow with increasing depth. Limited to drilling relatively shallow depth, small diameter boreholes. Extremely difficult to use in very coarse materials, i.e., cobbles and boulders. Large quantities of water required during drilling process. A water supply is needed that is under enough pressure to penetrate the geologic materials present. Use of water can affect groundwater quality in aquifer. Difficult-to-interpret sequence of geologic materials from cuttings. Presence of gravel or larger materials can limit drilling. Borehole can collapse before setting monitoring well if borehole uncased.

(b)



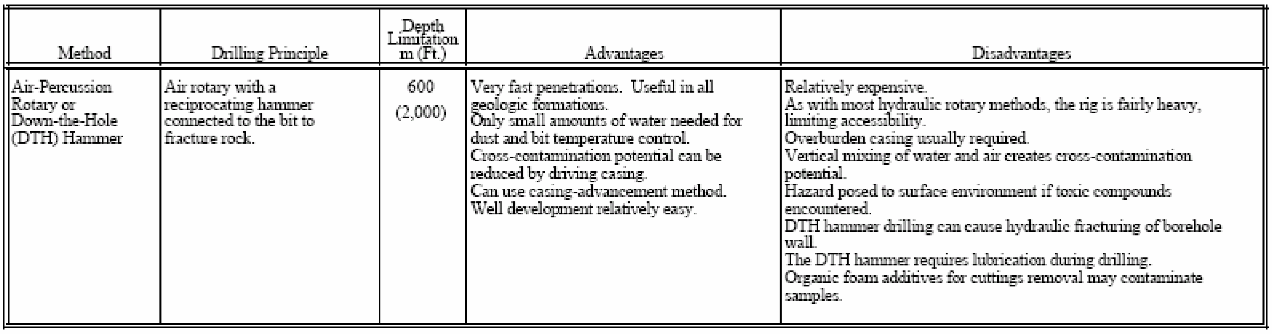
Method	Drilling Principle	Depth Limitation m (Ft.)	Advantages	Disadvantages
Cable-tool (percussion)	Hole created by dropping a heavy "string" of drill tools into well bore, crushing materials at bottom. Cuttings are removed occasionally by bailer. Generally, casing is driven just ahead of the bottom of the hole; a hole greater than 6 inches in diameter is usually made.	300+ (1,000 +)	Can be used in rock formations as well as unconsolidated formations. Can drill through cobbles and boulders and highly cavernous or fractured rock. Fairly accurate logs can be prepared from cuttings if collected often enough. Driving a casing ahead of hole minimizes cross-contamination by vertical leakage of formation waters and maintains borehole stability. Recovery of borehole fluid samples excellent throughout the entire depth of the borehole. Excellent method for detecting thin water-bearing zones. Excellent method for estimating yield of water-bearing zones. Excellent method for drilling in soil and rock where lost circulation of drilling fluid is possible. Core samples can be easily obtained. Excellent for development of a well.	The potential for cross-contaminated samples is very high. Decontamination can be difficult. Heavy steel drive pipe used to keep hole open and drilling "tools" can limit accessibility. Cannot run some geophysical logs due to presence of drive pipe. Relatively slow drilling method. Heavier wall, larger diameter casing than that used for other drilling methods normally used. Temporary casing can cause problems with emplacement of effective filter pack and grout seal. Heaving of unconsolidated sediment into bottom of casing can be a problem.
Mud Rotary	Rotating bit breaks formation; cuttings are brought to the surface by a circulating fluid (mud). Mud is forced down the interior of the drill stem, out the bit, and up the annulus between the drill stem and hole wall. Cuttings are removed by settling in a "mud pit" at the ground surface and the mud is circulated back down the drill stem.	1,500+ (5,000 +)	Drilling is fairly quick in all types of geologic materials, hard and soft. Borehole will stay open from formation of a mud wall on sides of borehole by the circulating drilling mud. Eases geophysical logging and well construction. Geologic cores can be collected. Can use casing-advancement drilling method. Borehole can readily be gravel packed and grouted. Virtually unlimited depths possible.	Expensive, requires experienced driller and fair amount of peripheral equipment. Completed well may be difficult to develop, especially small diameter wells, because of mud or filter-cake on wall of borehole. Lubricants used during drilling can contaminate the borehole fluid and soil/rock samples. Geologic logging by visual inspection of cuttings is fair due to presence of drilling mud. Beds of sand, gravel, or clay may be missed. Location of water-bearing zones during drilling can be difficult to detect. Drilling fluid circulation is often lost or difficult to maintain in fractured rock, root zones, or in gravels and cobbles. Difficult drilling in boulders and cobbles. Presence of drilling mud can contaminate water samples, especially the organic, biodegradable muds. Overburden casing usually required. Circulation of drilling fluid through a contaminated zone can create a hazard at the ground surface with the mud pit and cross-contaminate clean zones during circulation.

(c)



Method	Drilling Principle	Depth Limitation m (Ft.)	Advantages	Disadvantages
Reverse Rotary	Similar to hydraulic rotary method except the drilling fluid is circulated down the borehole outside the drill stem and is pumped up the inside, just the reverse of the normal rotary method. Water is used as the drilling fluid, rather than a mud, and the hole is kept open by the hydrostatic pressure of the water standing in the borehole.	1,500+ (5,000 +)	Drilling readily accomplished in soils and most hard rock. Drilling is relatively fast and for drilling large diameter boreholes. Borehole is accessible for geophysical logging prior to installation of well. Creates a very "clean" hole, not dirtied with drilling mud. Large diameter of borehole permits relatively easy installation of monitoring well. Can be used in all geologic formations. Very deep penetrations possible. Split-spoon sampling possible.	Drilling through cobbles and boulders may be difficult. Use of drilling fluids, polymeric additives, and lubricants can affect the borehole chemistry. A large water supply is needed to maintain hydrostatic pressure in deep holes and when highly conductive formations are encountered. Expensive--experienced driller and much peripheral equipment required. Hole diameters are usually large, commonly 18 inches or greater. Cross-contamination from circulating water likely. Geologic samples brought to surface are generally poor; circulating water will "wash" finer materials from sample.
Air Rotary	Very similar to hydraulic rotary, the main difference is that air is used as the primary drilling fluid as opposed to mud or water.	1,500+ (5,000 +)	Can be used in all geologic formations; most successful in highly fractured environments. Useful at most any depth. Drilling in rock and soil is relatively fast. Can use casing-advancement method. Drilling mud or water not required. Borehole is accessible for geophysical logging prior to monitoring well installation. Well development relatively easy.	Relatively expensive. Cross-contamination from vertical communication possible. Air will be mixed with the water in the hole and blown from the hole, potentially creating unwanted reactions with contaminants; may affect "representative" samples. Air, cuttings and water blown from the hole can pose a hazard to crew and surrounding environment if toxic compounds encountered. Compressor discharge air may contain hydrocarbons. Organic foam additives to aid cuttings removal may contaminate samples. Overburden casing usually required.
Sonic (vibratory)	Employs the use of high-frequency mechanical vibration to take continuous core samples of overburden soils and most hard rock.	150 (500)	Can obtain large diameter, continuous and relatively undisturbed cores of almost any soil material without the use of drilling fluids. Can drill through boulders, wood, concrete and other construction debris. Can drill and sample most softer rock with high percentage of core recovery. Drilling is faster than most other methods. Reduction of IDW.	Rock drilling requires the addition of water or air or both to remove drill cuttings. Extraction of casing can cause smearing of borehole wall with silt or clay. Extraction of casing can damage well screen. Equipment is not readily available and is expensive.

(d)



Method	Drilling Principle	Depth Limitation m (Ft.)	Advantages	Disadvantages
Air-Percussion Rotary or Down-the-Hole (DTH) Hammer	Air rotary with a reciprocating hammer connected to the bit to fracture rock.	600 (2,000)	Very fast penetrations. Useful in all geologic formations. Only small amounts of water needed for dust and bit temperature control. Cross-contamination potential can be reduced by driving casing. Can use casing-advancement method. Well development relatively easy.	Relatively expensive. As with most hydraulic rotary methods, the rig is fairly heavy, limiting accessibility. Overburden casing usually required. Vertical mixing of water and air creates cross-contamination potential. Hazard posed to surface environment if toxic compounds encountered. DTH hammer drilling can cause hydraulic fracturing of borehole wall. The DTH hammer requires lubrication during drilling. Organic foam additives for cuttings removal may contaminate samples.

Table 1.1-2: Performance of Drilling Methods in Various Types of Geologic Formations

	Drilling Method		
Type of Formation	Cable Tool	Rotary	Rotary Percussion[a]
Dune sand	Difficult	Rapid	NR
Loose sand and gravel	Difficult	Rapid	NR
Quicksand	Difficult, except in thin streaks. Requires a string of drive pipe.	Rapid	NR
Loose boulders in alluvial fans or glacial drift	Difficult; slow but generally can be handled by driving pipe	Difficult, frequently impossible	NR
Clay and silt	Slow	Rapid	NR
Firm shale	Rapid	Rapid	NR
Sticky shale	Slow	Rapid	NR
Brittle shale	Rapid	Rapid	NR
Sandstone, poorly cemented	Slow	Slow	NR
Sandstone, well cemented	Slow	Slow	NR
Chert nodules	Rapid	Slow	NR
Limestone	Rapid	Rapid	Very rapid
Limestone with chert nodules	Rapid	Slow	Very rapid
Limestone with small cracks or fractures			Very rapid
Limestone, cavernous	Rapid	Slow to impossible	Difficult
Dolomite	Rapid	Rapid	Very rapid
Basalts, thin layers in sedimentary rocks	Rapid	Slow	Very rapid
Basalts, thick layers	Slow	Slow	Rapid
Metamorphic rocks	Slow	Slow	Rapid
Granite	Slow	Slow	Rapid

[a] NR: not recommended.

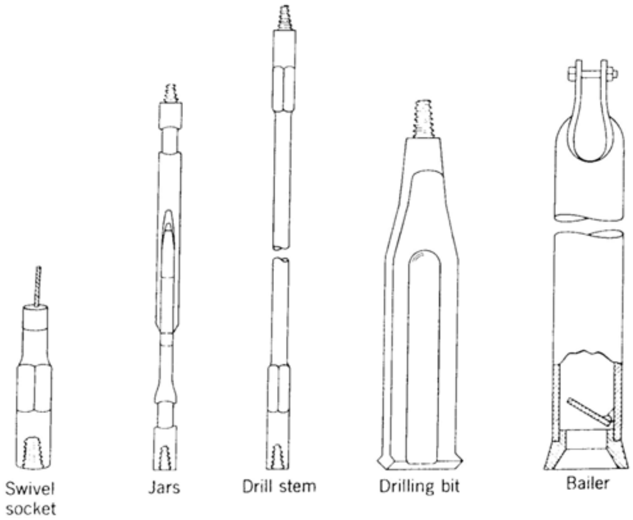


Figure 1.1-1: Basic Well Drilling Tools for the Cable Tool Method

Figure 1.1-2: Cable Tool Rig in Operation

During drilling the tools make 20-40 stokes per minute, ranging from 40 to 100 cm in length. The drilling line is rotated so that the bit forms a round hole, and additional line is let out as needed so that the bit will always strike the bottom of the hole. Water should be added to the hole if none is encountered to form a paste with the cuttings, thereby reducing friction on the falling bit. After the bit has cut 1 or 2 m through a formation, the string of tools is lifted to the surface and the hole is bailed. In unconsolidated formations, casing should be maintained to near the bottom of the hole to avoid caving.

The cable tool rig is highly versatile in its ability to drill satisfactorily over a wide range of geologic conditions[1]. Its major drawbacks are its slower drilling rate, its depth limitation, the necessity of driving casing coincidentally with drilling in unconsolidated materials, and the difficulty of pulling casing from deep holes. The simplicity of design, ruggedness, and ease of maintenance and repair of the rigs and tools are important advantages in isolated areas. Also, less water is required for drilling than with other methods, a matter of concern in arid and semiarid regions. Furthermore, sampling and formation logging are simpler than more accurate with a cable tool rig.

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[1] In particular, cable tool rigs can be drill through boulders and fractured, fissured, broken, or cavernous rocks, which often are beyond the capabilities of other types of equipment.

b. Rotary Method

A rapid method for drilling in unconsolidated strata is the rotary method. Deep wells up to 45 cm in diameter, and even lager with a reamer, can be consolidated. The method operates continuously with a hollow rotating bit through which a mixture of clay and water, or drilling mud, is forced. Material loosened by the bit is carried upward in the hole by the rising mud. No casing is ordinarily required during drilling because the mud forms a clay lining, or mud cake, on the wall of the well by filtration. This seals the walls, thereby preventing caving, entry of groundwater, and loss of drilling mud.

Drilling bits are available in various forms; a group of conical roller gears with teeth that scrape, grind, and fracture the rock is common design (see Figure 1.1-3). The typical string of tools consists of a bit, a drill collar (which adds weight to the bit and aids in maintaining hole alignment), and a drill pipe that extends to the ground surface. The upper end of the drill pipe is attached to the kelly – a square section of drill rod. The drill is turned by a rotating table that fits closely around the kelly and allows the drill rod to slide downward as the hole deepens. The drilling rig for a rotary outfit consists of a derrick, or mast, a rotating table, a pump for drilling mud, a hoist, and the engine.

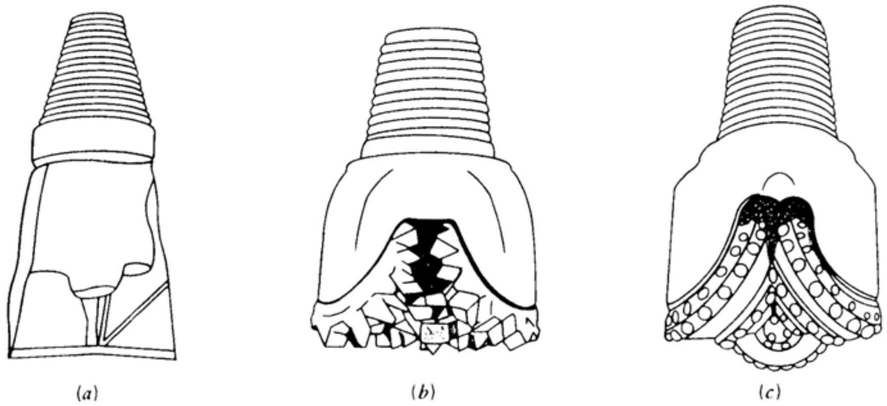


Figure 1.1-3: Example of Rotary Drill Bits

(a) Fishtail bit, (b) Cone-type rock bit, (c) Carbine button bit

Drilling mud consists of a suspension of water, bentonite, clay, and various organic additives. Maintenance of the correct mud in terms of weight, viscosity, jelling strength, and low percentage of suspended solids is important for trouble-free drilling. Organic additives that degrade with time and thereby cause the mud cake to break down within a few days are recent innovation. The drilling mud leaves the drill pipe through the bit where it cools and lubricates the cutting surface, entrains drill cuttings, and carries the drill cuttings upward within the annular space between drill pipe and hole wall as the fluid returns to ground surface (see Figure 1.1-4). The drilling mud then overflows into a ditch and passes into a settling pit. Here the cuttings settle out; thereafter, the mud is picked up by the pump for recirculation in the hole.

Rotary drilling is employed for oil wells and its application to water-well drilling is steadily increasing. Advantages are the rapid drilling rate, the avoidance of placement of casing during drilling, and the convenience for electric logging. Disadvantages include high equipment cost, more complex operation, the need to remove mud cake during well development, and the problem of lost circulation in highly permeable or cavernous geologic formations.

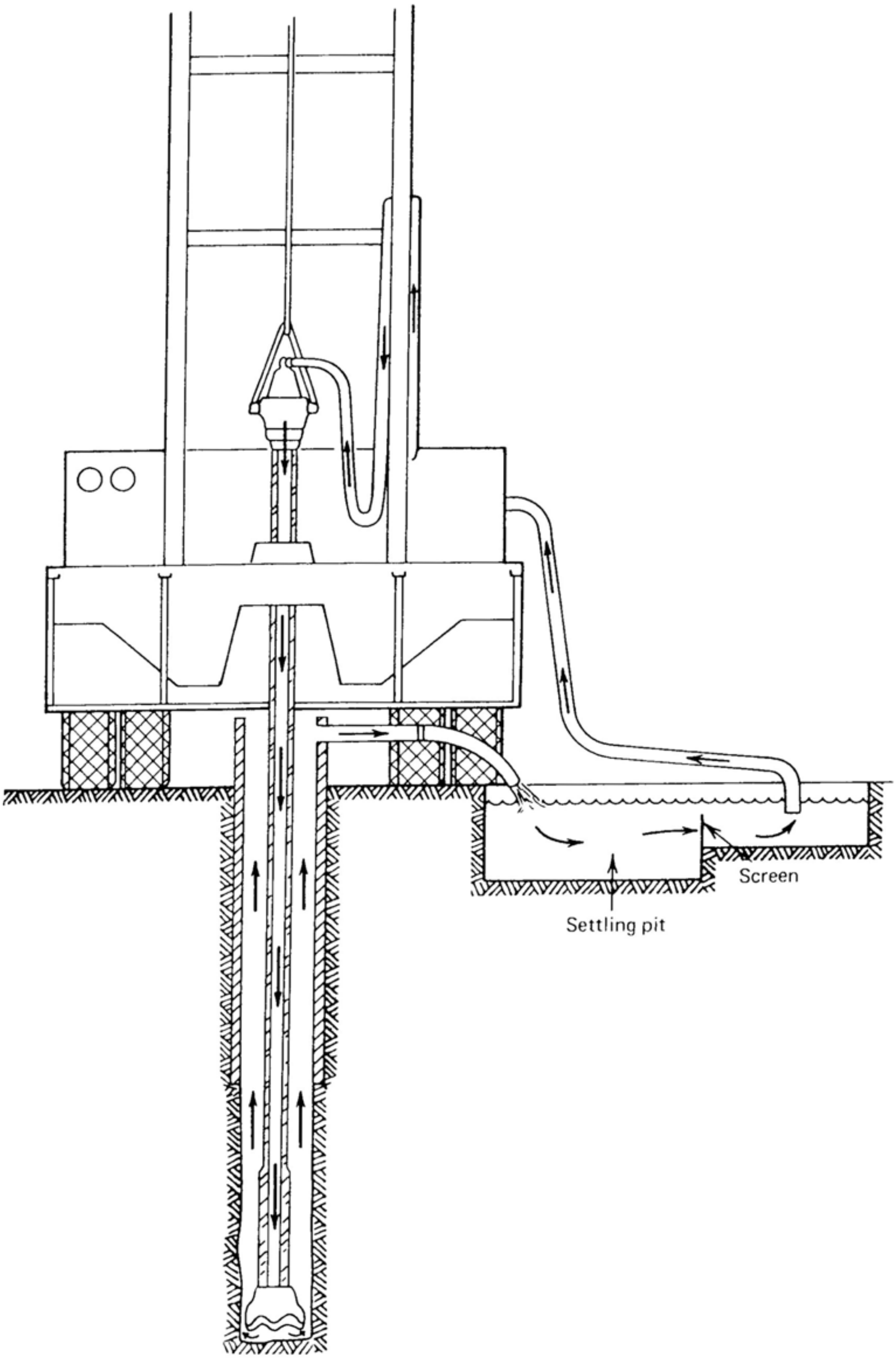


Figure 1.1-4: Drilling Mud Circulation system for the Rotary Method

c. Air Rotary Method

Rotary drilling can also be accomplished with compressed air in place of drilling mud. The technique is rapid and convenient for small-diameter holes in consolidated formations where a clay lining is unnecessary to support the walls against caving. Large-diameter holes can be drilled by employing foams and other air additives. Drilling depths can exceed 150 m under favorable circumstances. An important advantage of the air rotary method is its ability to drill through fissured rock formations with litter or no water required.

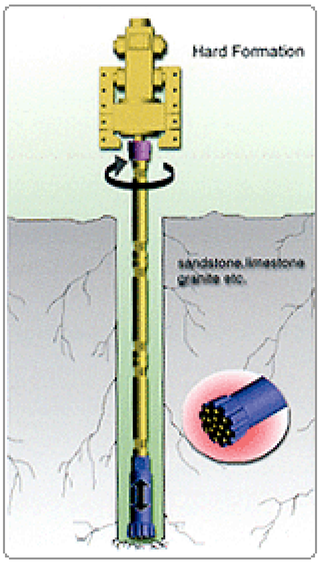
d. Rotary-Percussion Method and Down the Hole Drilling Method

A recently developed rotary-percussion procedure using air the drilling fluid provides the fastest method for drilling in hard-rock formations. A rotating bit, with the action of pneumatic hammer, delivers 10 to 15 impacts per second to the bottom of the hole. Penetration rates of as much as 0.3 m/min. have been achieved. Where caving formations or large quantities of water are encountered, a change to conventional rotary drilling with mud usually becomes necessary.

DTH (Down the Hole) Drilling Method

The down-the-hole hammer drill is a pneumatically operated bottom-hole drill that efficiently combines the hitting action, similar to that of cable tool drilling, with the turning action of rotary drilling. The pneumatic drill can be used on any standard rotary rig with an integral or auxiliary air compressor of sufficient capacity.

- It is used for fast and economical drilling of medium to extremely hard formations.



Fast penetration results from the air piston blows transmitted directly to the bit, so practically no energy is wasted in chewing up cuttings. A straight hole is assured by short, rapid blows that minimize the effect of dipping and broken formations. Down-the-hole hammer drilling is by far the fastest method of penetration in hard rock material. The bit is turned slowly (10 to 15 RPM) by the same method that rotates the drill bit in the mud or air drilling operation.

HP: Royall Pump & Well Company - Powhatan

1.2 Well Completion

After a well has been drilled, it must be completed. This can involved placement of casing, cementing, placement of well screens, and gravel packing; however, wells in hard-rock formations can be left as open holes so that these components may not be required.

a. Well Casings

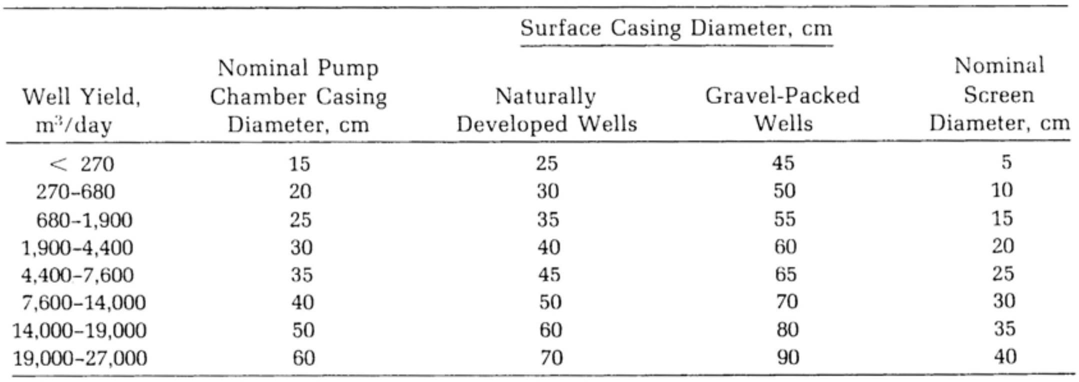
Well casing serves as a lining to maintain an open hole from ground surface to the aquifer. It seals out surface water and any undesirable groundwater and also provides structural support against caving materials outside the well. Materials commonly employed for well casings are wrought iron, alloyed or unalloyed steel, ingot iron, and PVC (polyvinyl chloride). Joints normally consist of threaded couplings or are welded, the object being to secure watertightness. In cable-tool drilling, the casing is driven into place; in rotary methods, the casing is smaller than the drilled hole and hence can be lowered into place.

Surface casing is installed from ground surface through upper strata of unstable or fractured materials into a stable and, if possible, relatively impermeable material. Such surface casing serves several purposes, including:

- supporting unstable materials during drilling
- reducing loss of drilling fluids
- facilitating installation or removal of other casing
- aiding in placing a sanitary seal
- serving as a reservoir for a gravel pack

This casing may be temporary during drilling or it may be permanent. Recommended minimum diameters of surface casing are given in Table 1.2-1.

Table 1.2-1: Recommended Minimum Diameters for Well Casing and Screens



Well Yield, m^3/day	Nominal Pump Chamber Casing Diameter, cm	Surface Casing Diameter, cm Naturally Developed Wells	 Gravel-Packed Wells	Nominal Screen Diameter, cm
< 270	15	25	45	5
270-680	20	30	50	10
680-1,900	25	35	55	15
1,900-4,400	30	40	60	20
4,400-7,600	35	45	65	25
7,600-14,000	40	50	70	30
14,000-19,000	50	60	80	35
19,000-27,000	60	70	90	40

b. Cementing

Wells are cemented in the annular space surrounding the casing to prevent entrance of water of unsatisfactory quality, to protect the casing against exterior corrosion, and/or to stabilize caving rock formations. Cement grout, consisting of a mixture of cement and water and sometimes various additives, can be placed by a dump bailer, by a tremie pipe, or by pumping. It is important that the grout be introduced at the bottom of the space to be grouted to ensure that the zone is properly sealed.

c. Screens

In consolidated formations, where the material surrounding the well is stable, groundwater can enter directly into an uncased well. In unconsolidated formations, however, wells are equipped with screens. These stabilize the sides of the hole, prevent sand movement into the well, and allow a maximum amount of water to enter the well with a minimum of hydraulic resistance.

Screens are available in a range of diameters; selection of screen diameter should be made on the basis of the desired well yield and aquifer thickness. Recommended minimum screen diameters are included in Table 1.2-1.

d. Gravel Packs

A gravel-packed well is one containing an artificially placed gravel screen or envelope surrounding the well screen (see Figure 1.2-1). A gravel pack (1) stabilizes the aquifer, (2) minimizes sand pumping, (3) permits use of a large screen slot with a maximum open area, and (4) provides an annular zone of high permeability, which increases the effective radius and yield of the well. Maximum grain size of a pack should be near 1.0 cm, while the thickness should be in the range of 8 to 15 cm.

Various formulas for relating gravel pack grain-size gradations to aquifer grain-size gradations have been developed. Criteria conforming to U.S. Bureau of Reclamation field experience are summarized in Table 1.2-1. The selected gravel should be washed and screened siliceous material that is rounded, abrasive-resistant, and dense. Gravel should be placed in such a manner as to ensure complete filling of the annular space and to minimize segregation. A common procedure is to extend two tremie pipes to the bottom of the well on opposite sides of the screen. Gravel is poured, washed, or pumped into the tremie pipes; these are then withdrawn in stages as the pack is placed. In sandy aquifers, where a gravel pack is most essential, deep wells should be constructed by the rotary method etc. The drilling fluid should be circulated and diluted with water before the gravel is introduced.

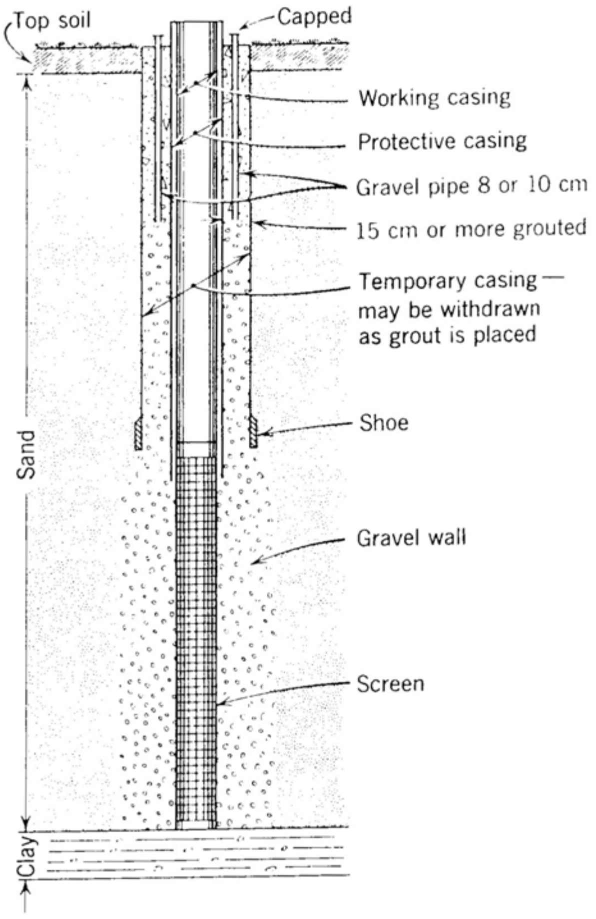


Figure 1.2-1: Vertical Cross-section of a Gravel-packed Well