4.5 Investigation techniques and equipment

The MIU Project also has the role of testing new investigation techniques and equipment that may be useful for all phases of the investigations. Some techniques and equipment have been or are in the process of being developed by TGC. If the equipment trials or the investigation results do not meet expectations or needs of the individual study field (for example data accuracy or instrument precision and reliability of equipment), the techniques and equipment may be modified to improve performance.

4.5.1 Techniques and equipment for borehole investigations

The MIU Project has adopted an operating guideline to use only fresh water as drilling fluid. Additives such as drilling mud are avoided so that initial permeability of the rock mass and the hydrochemical properties of groundwater are disturbed as little as possible. However, boreholes are less stable and potentially prone to collapse when fresh water alone is used. Therefore, drilling techniques to minimize and prevent collapse and expertise in their use are being developed.

4.5.1.1 Drilling system using a reverse aeration, wire-line method

In order to minimize the disturbance of the hydrogeological properties of the rock mass and hydrochemical properties of groundwater, it is desirable to use fresh water as drilling fluid. However, boreholes drilled without drilling mud are more prone to collapse. One alternative drilling method investigated is the reverse aerated, wire-line method. The method allows use of fresh water for drilling and removal of drilling fluids/rock chips/rock flower by directing fluids into the center of drill rods, which prevents contact with the borehole wall and minimizes collapse of the wall and plugging of open zones (Figure 4.71).

This method was designed in 1997 FY (87) and the overall drilling system in 1999 FY (88).

4.5.1.2 Partial casing insertion equipment

Partial casing insertion equipment was developed to cope with partial collapse of boreholes. This equipment consists of a partial reaming bit, a casing insertion unit and the partial casing (89). It can be used for drilling of new boreholes as well as maintaining and reaming existing boreholes (Figure 4.72).

The partial reaming bit was manufactured in 1996 FY (90). An application test was carried out (87) and the casing insertion unit was manufactured in 1997 FY. Also in 1997, the required equipment was assembled and an operational application test on the ground was carried out (87). In 1999 FY, an overall, trail application test was carried out using the partial reaming bit, the casing insertion unit and the partial casing. Problems with insertion were found by BTV investigation to be at that the lower end of the partial casing set, which was bent to the inside of the borehole and thus prevented the casing from fitting the rock mass adequately. In the future, a method to cut off the bent casing is expected to be developed (88).

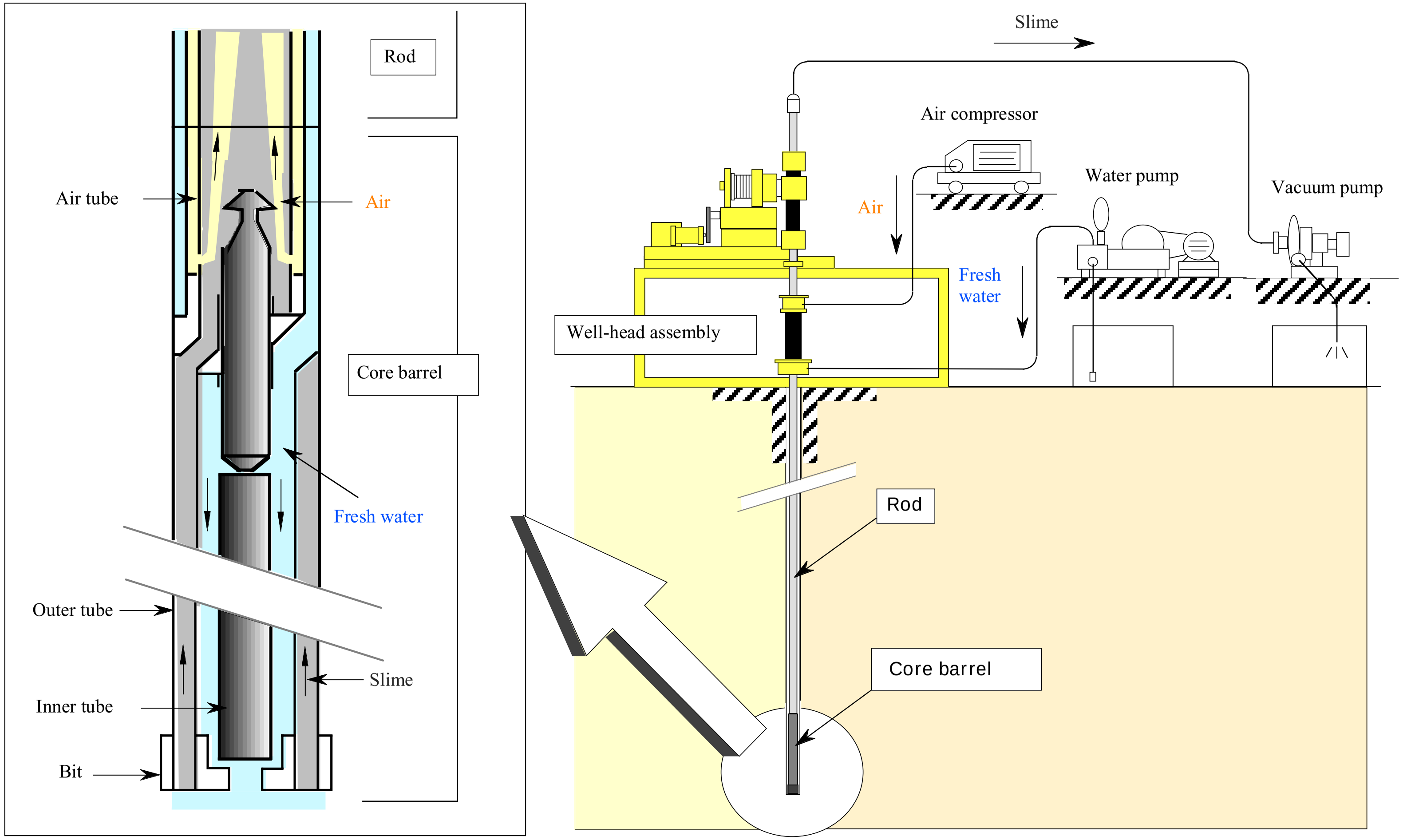

Figure 4.71 Drilling system using reverse aerated wire-line method

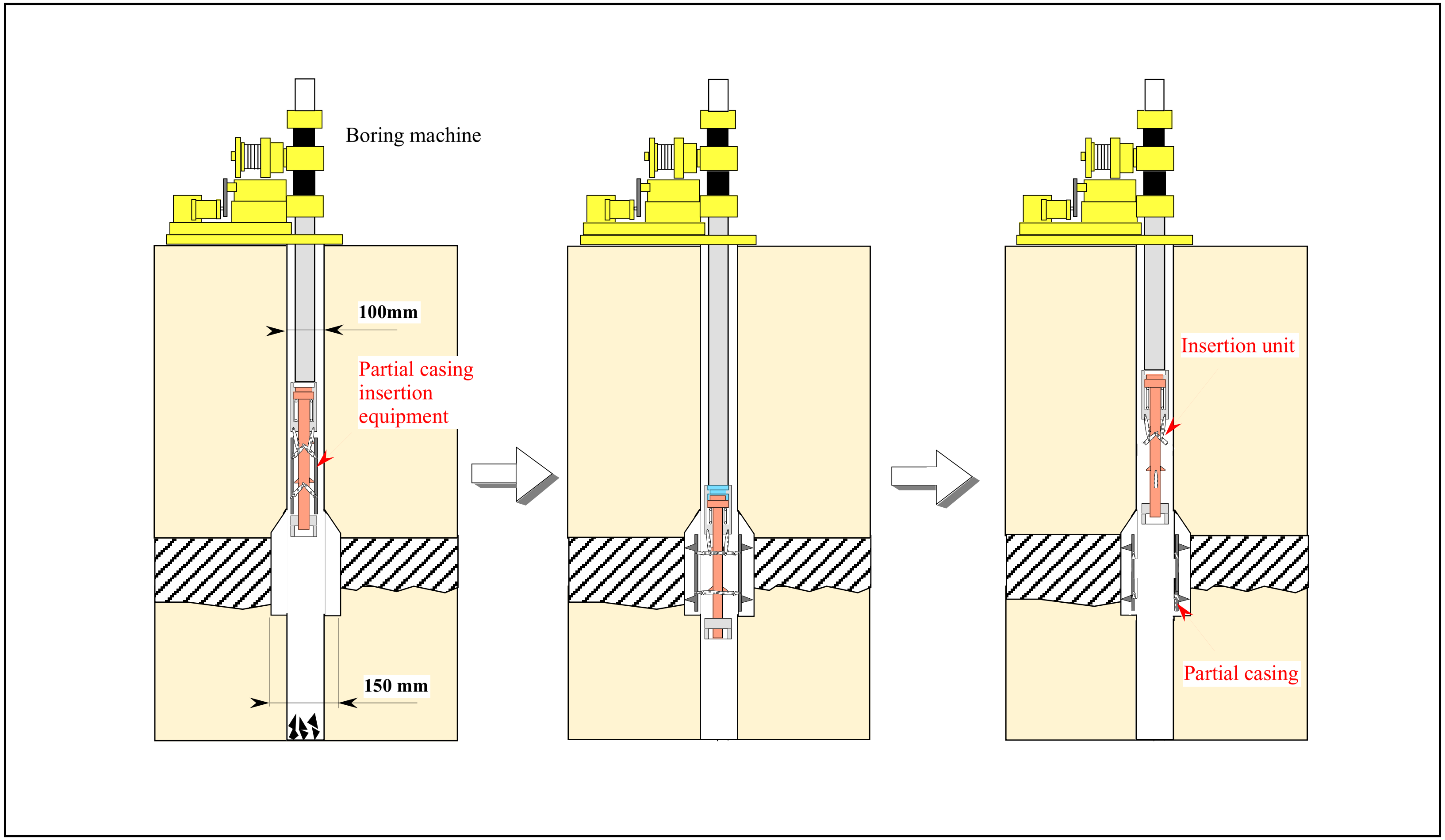

Figure 4.72 Partial casing insertion equipment

4.5.2 Techniques and equipment for geological investigations

4.5.2.1 Seismic tomography

The development of seismic tomography for use in 1,000 m-deep boreholes was in progress to understand the extent of discontinuity planes deep underground. The work in the reporting period consists of the development of an in-hole nondestructive seismic source (sparker) that would work without enducing any damage to the surrounding borehole wall and the development of data analysis techniques.

The in-borehole sparker was designed and assembled in 1997 FY. An application test of the assembled equipment was carried out in 1998 FY [(89, 91)]. Subsequently, application tests were carried out in MIU-1 and 2 to the depth of 1,000 m in 1999 FY [(88)]. In addition, the development of a data analysis technique called "full-wave form inversion" was carried out to improve the resolution of signals.

Details of data acquisition in the application tests are shown in Table 4.38. Results of the application tests in the Toki Granite are as follows.

- · Using the sparker, tomographic data were obtained with cross-hole intervals of about 100 m and with a target depth of 1,000 m.
- · Based on the application test carried out in 1998FY, it was estimated that the maximum distance that allows distinguishing the P-wave generated by the sparker from noise was about 260 m. However, the distance was reduced to about 150 m, due to excessive noise during the test carried out in 1999.
- · In order to improve the maximum distance that a P-wave can be recognized, a stacking test with several oscillations was carried out. This test resulted in an improvement of signal to noise (S/N) ratio. For example, Figure 4.73 illustrates an initial P-wave made recognizable by a 32-times stacking test. The maximum distance between the sparker and the receiver was some 240 m.

An initial travel time tomographic analysis was carried out by determining the arrival time of the initial P-wave. Figure 4.74 shows the result of a P-wave velocity structural analysis. The grid size for analysis was 2.5 m (horizontal)$\times$3 m (vertical). The tomographic section was divided into shallow areas with higher velocity (5.3 km/s.) and deeper areas with lower velocity (4.9 km/s.) at about the 850 m depth. This shows a trend coincident with the results of seismic wave velocity logging. The Tsukiyoshi Fault intersected by MIU-2 at around 900 m depth was not recognized as a structure with a sharp velocity contrast against the surrounding rock mass.

As part of the development of analytical techniques for producing seismic tomographic data, an applicability study of full-wave form inversion analysis to actual data was carried out. The data (Table 4.38) obtained by sparker application tests in 1999 FY was used for this study.

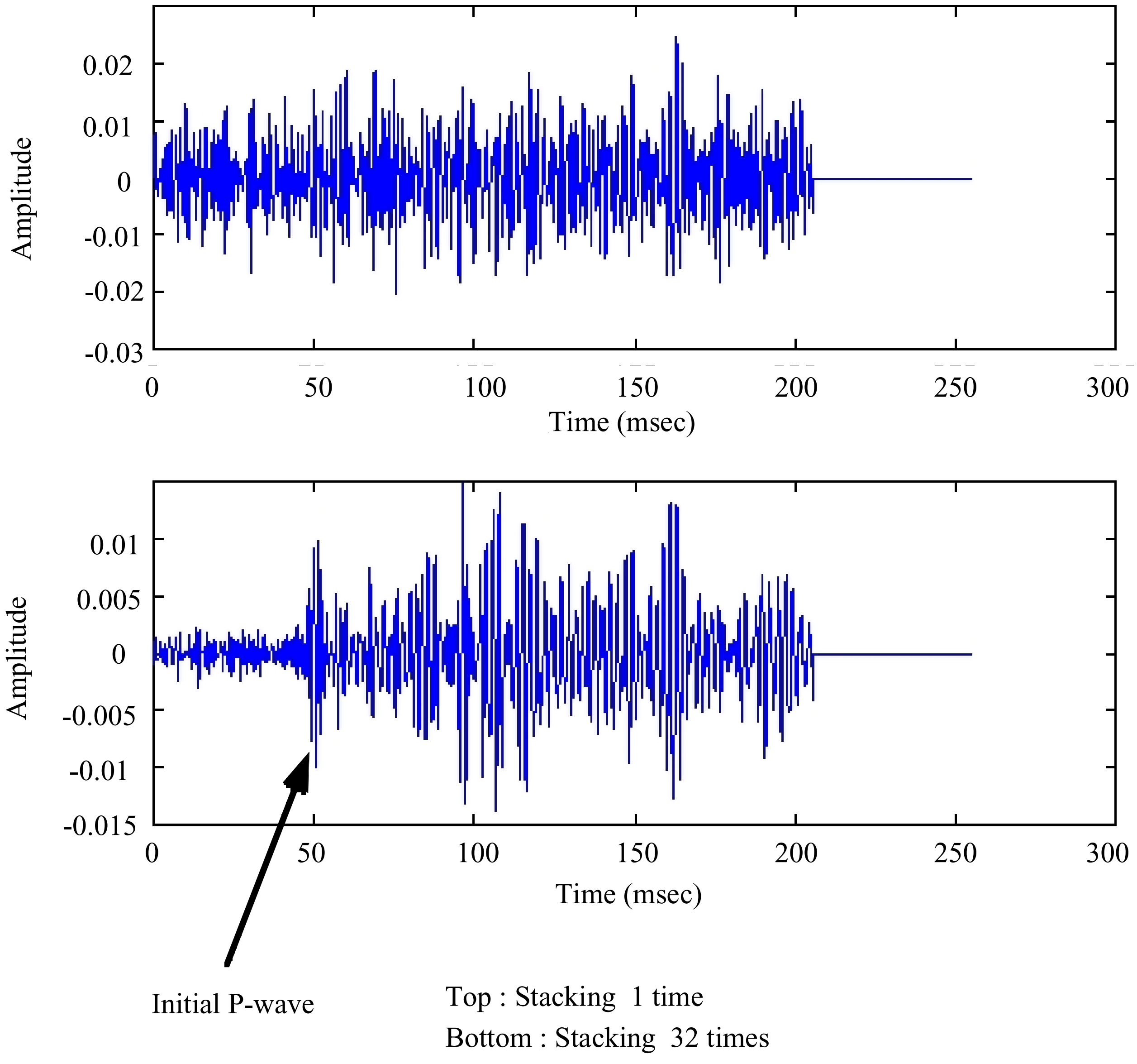

Figure 4.73 Results of stacking test (example)
(depth of sparker : 450 m, depth of receiver : 230 m)

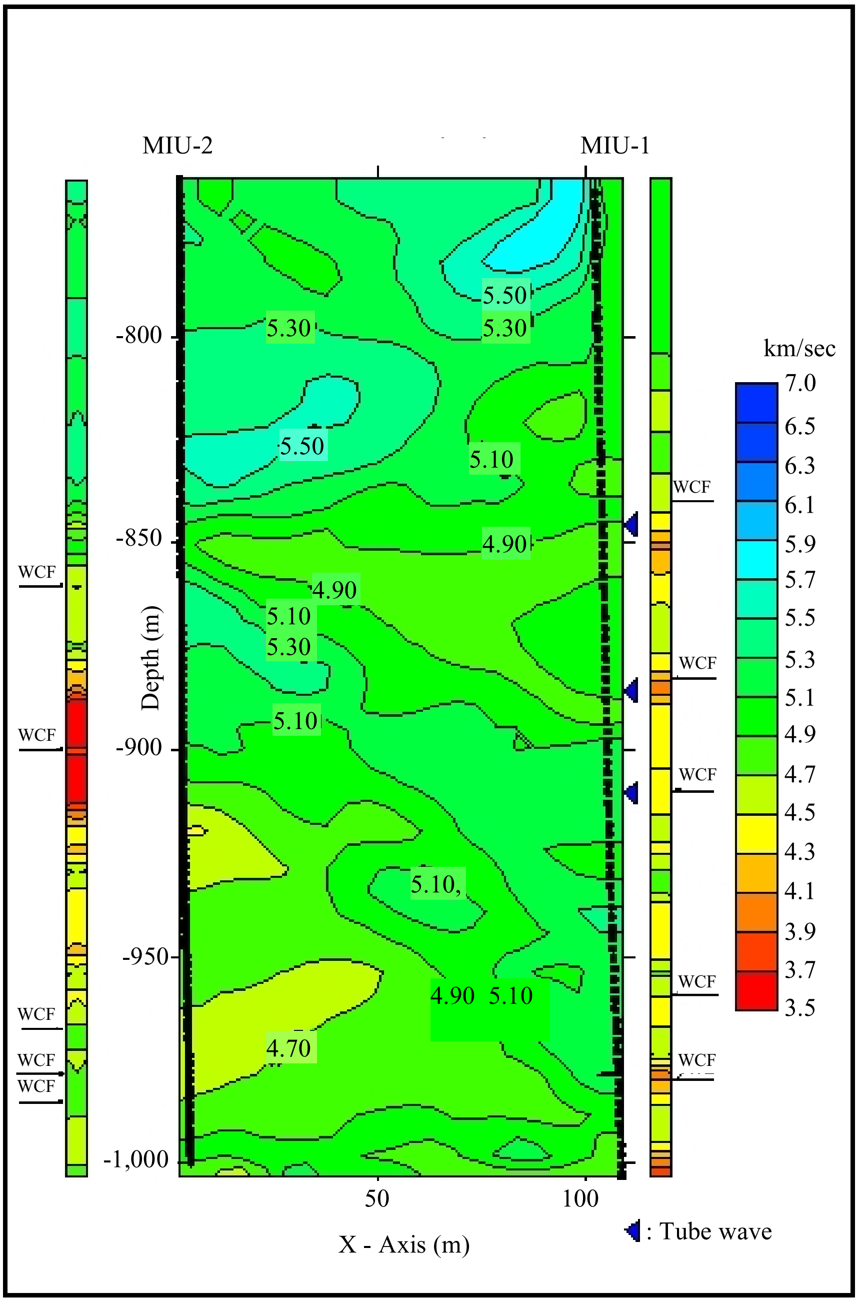

Figure 4.74 The result of P-wave velocity distribution analysis

Table 4.38 Details of seismic tomography

	1998 FY (AN-1, 3)	1999 FY (MIU-1, 2)
Borehole interval	about 36 m	about 95 m
Data acquisition depth	30 m to 364 m	762 m to 1,000 m (Signal) 762.5 m to 1,000 m (Receiver)
Sparker interval/number	1 m/335 points (AN-1)	2 m/120 points (MIU-2)
Receiver interval/number	2 m/168 points (AN-3)	2.5 m/96 points (MIU-1)
Data acquisition number	56,280 (335×168)	11,520 (120×96)
Data length (Recording time)	192 msec	256 msec
Sampling rate	0.125 msec	0.125 msec

Scope of the analysis is as follows.

- · Digital simulation for verifying a series of analysis codes
- · Study the preliminary processing of data used for full-wave inversion analysis
- · Implementation of the full-wave inversion analysis and determination of future tasks

The results of full-wave inversion analysis are shown in Figure 4.75. The grid size for analysis measured 25-cm×25 cm and featured a higher resolution than the conventional initial travel time tomographic analysis with a resolution of several meters. Though vertical variations in velocity show a similar trend to the results of seismic wave velocity logging, only results obtained by a nearly horizontal sparker-receiver pair are usable for analysis due to excessively large noise. As a result, horizontal structures are most likely to be detected. In the future, examination of the application limitation with respect to noise in the full-waveform inversion analysis is expected. Also, the possibility of improvement in the analysis method is needed.

4.5.3 Techniques and equipment for hydrogeological investigations

4.5.3.1 Hydraulic test equipment for depths up to 1,000 m

In order to understand groundwater hydrogeology deep underground, the ability to determine the hydrogeological properties of relatively impermeable rock masses, with hydraulic conductivities of less than 10^{-8} m/s is necessary. Such a rock mass was traditionally classified as impermeable in civil engineering practice. Also, the equipment must be able to acquire accurate data under potentially high temperature and pressure conditions because the target depths exceed hundreds of meters. TGC has been developing equipment allowing in-situ permeability tests on highly impermeable rock masses down to 1,000 m depth (Figure 4.76) (92,93). This equipment was assembled in 1997 FY, and is being used in the MIU Project and the RHS Project.

The hydrogeological test equipment consists of a downhole unit suspended from stainless steel rods and the surface equipment with cable reels and data acquisition and processor control units. The downhole unit consists of a multi-packer measurement unit with sensors, a pumping unit and a BTV camera. An inner probe can be lowered on an umbilical cable inside the stainless steel suspension rods into the measuring intervals. Use of the stainless-steel pipe provides high tensile strength to the downhole unit and can improve recovery potential in event of borehole wall stability problems. This equipment is useful for the

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(a) A transient slug test method
(b) A pulse method developed for testing of very low permeability rocks
(c) A pumping test under steady state conditions

By combined use of these methods, a wide range of hydraulic conductivities from 10^{-6} to 10^{-12} m/s can be measured.

The most prominent feature of this equipment is the five multipackers and the BTV at the tip of the equipment string. With five multipackers, it is possible to measure different size test intervals without resetting the equipment. The test intervals can be changed freely by selectively setting the packers between 2 m and 14 m. By measuring pore water pressure and temperature outside of the test interval, it is possible to check if the packers work efficiently. These functions are extremely useful to ensure the quality of the test results. Also, using the BTV, allows the monitoring of the rock conditions in front of and at the sides of the equipment in real time. This enables the confirmation of the rock conditions for packer placement. Furthermore, even when the data has to be collected from a narrow fracture zone, the equipment can be located confidently.

The equipment was improved in 1998 FY (89) for installations in a curved borehole: for example, by adding a centralizer. This improvement is shown in Figure 4.77.

4.5.4 Techniques and equipment for hydrochemical investigations

4.5.4.1 Water sampling equipment for depths of 1,000 m

For fast and precise understanding of hydrochemical properties of groundwater between the ground surface and deep underground, water sampling equipment was being developed (93, 94). The target depth was 1,000 m and the aim was to minimize further disturbance of the properties of geological environment caused by borehole drilling. This equipment was developed by 1997 FY and has been used for the MIU Project and the RHS Project.

The equipment comprises surface equipment, a connector and underground tools (Figure 4.78). All functions related to water sampling are located in the in-hole section. Installation through drill rods or casing was adopted as the basic procedure, as a precaution against borehole collapse, similar to the above hydraulic test equipment for depths to 1,000 m.

Batch water sampling function was adopted so that sampling in a confined inert state, to ensure maintenance of in situ chemical properties, was possible. Also, the capability for continuous purging of groundwater with a pump was added to enhance the sampling efficiency.

Furthermore, the equipment was improved in 1998 FY (89) for coping with a curved borehole, for example, by adopting flexible joints. The improvement is shown in Figure 4.79.

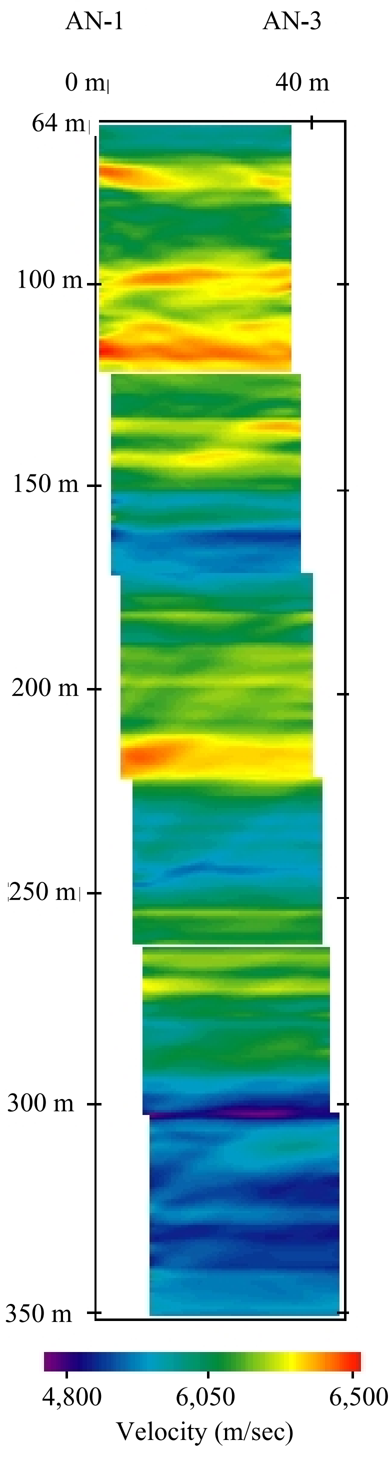
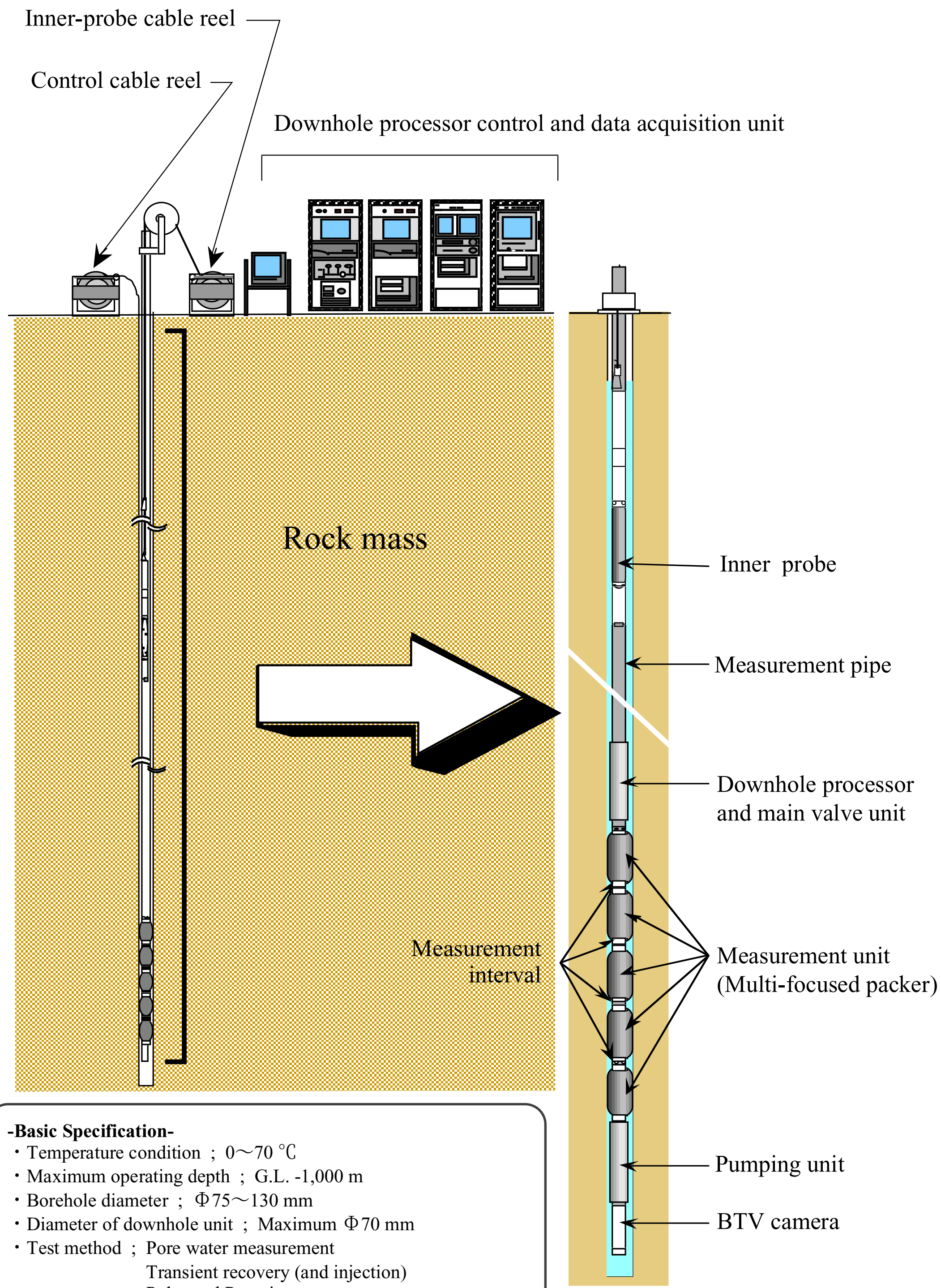


Figure 4.75 The result of full wave-form inversion analysis



-Basic Specification-

- Temperature condition ; 0～70 ℃
- Maximum operating depth ; G.L. -1,000 m
- Borehole diameter ; Φ75～130 mm
- Diameter of downhole unit ; Maximum Φ70 mm
- Test method ; Pore water measurement
  Transient recovery (and injection)
  Pulse and Pumping
- Measurement range of hydraulic conductivity ; 10^{-6}～10^{-12} m/s
- Innovative features ; Borehole television camera

Figure 4.76 Hydraulic test equipment for depths of up to 1,000 m

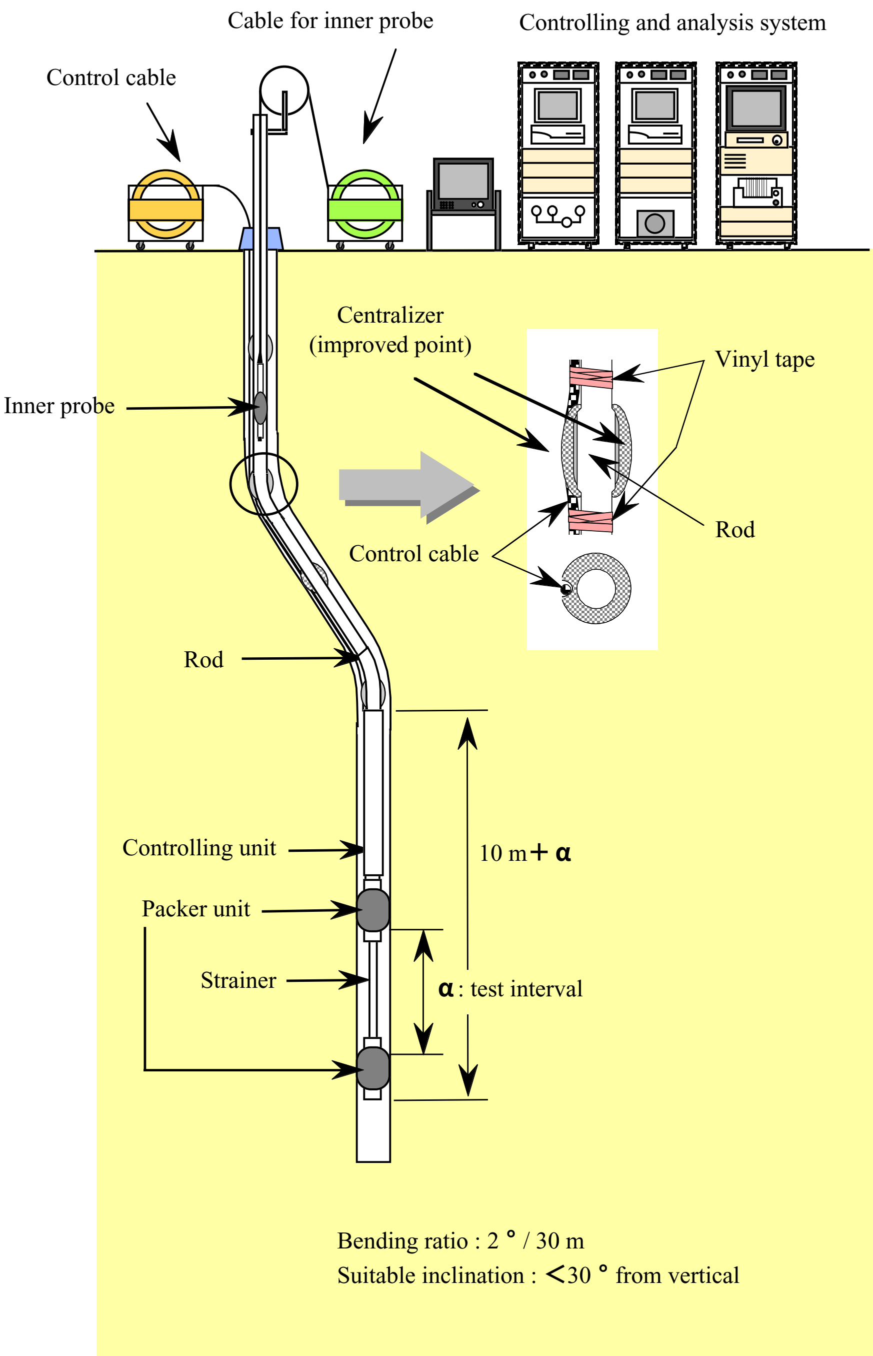


Figure 4.77 Hydraulic test equipment for depths of up to 1,000 m (improved for curved borehole)

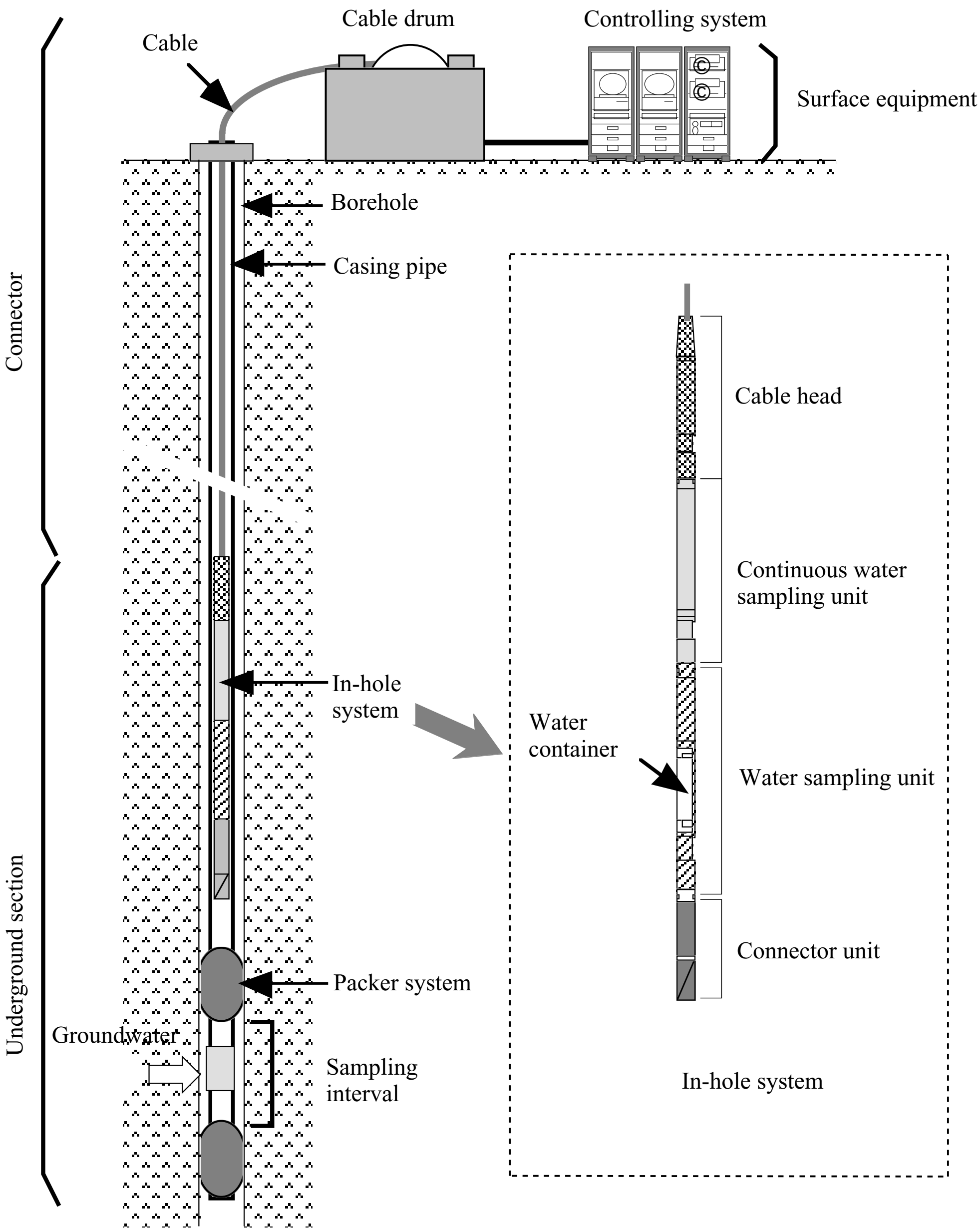


Figure 4.78 Water sampling equipment for depths of up to 1,000 m

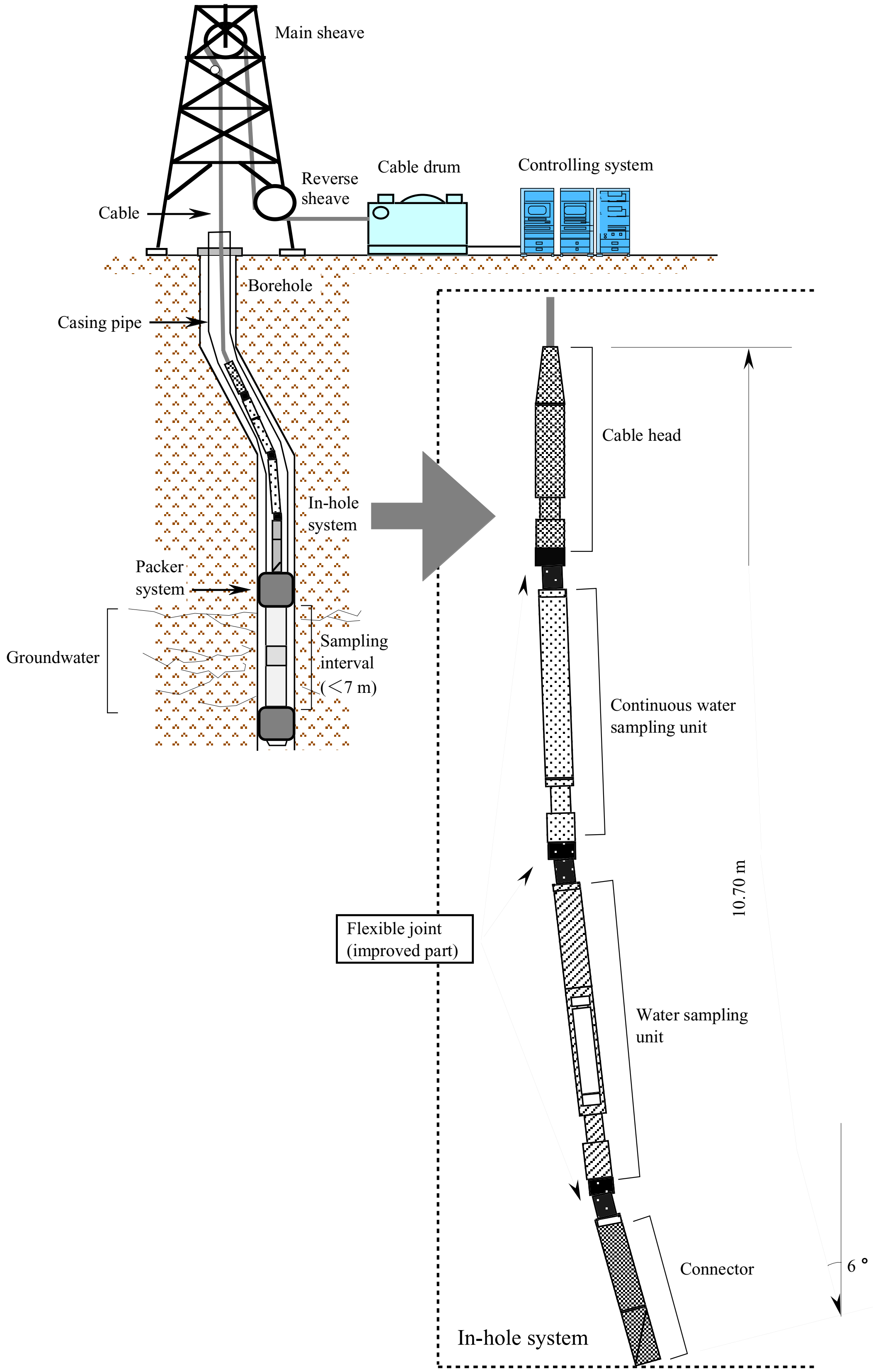


Figure 4.79 Water sampling equipment for depths of up to 1,000 m (improved for curved borehole)

4.5.4.2 Geochemical logging unit

The geochemical logging unit was developed for in-situ acquisition of physico-chemical parameters of groundwater, including pH, redox potential, electrical conductivity, and sulphide ion concentration and water temperature.

This unit was mounted on the water sampling equipment for depths to 1,000 m, allowing real-time data acquisition of the physico-chemical parameters of groundwater during continuous water sampling operations. Thus, it allows confirmation of the in situ chemical condition of groundwater, and in particular, the replacement of drilling fluid in boreholes by groundwater flowing into the sampling interval isolated by double packers. Also, it enables the accurate timing of water sampling [(94)].

4.5.5 Techniques and equipment for rock mechanical investigations

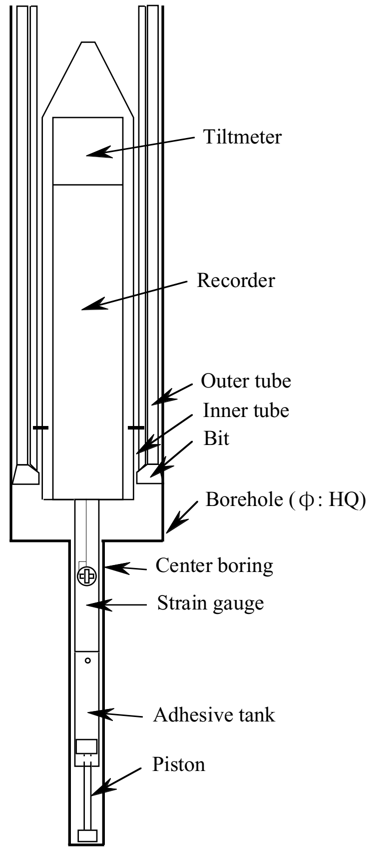
4.5.5.1 In situ stress measuring equipment for depths to 1,000 m

Determination of in situ stress in the rock mass is necessary because the stress establishes a boundary condition indispensable for optimized designing and stability assessment of the MIU Project's research galleries and for numerical analysis of rock mass response to shaft excavation.

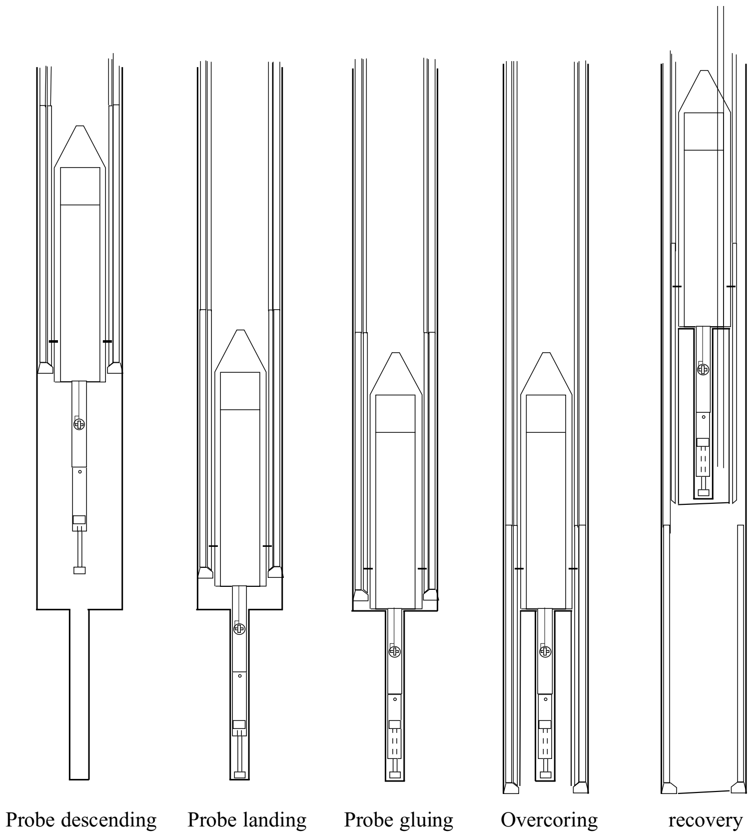
In situ stress determination techniques in general-use are classified into in situ techniques such as borehole methods (e.g. hydraulic fracturing and over-coring techniques) and laboratory techniques using recovered core from boreholes or outcrops (e.g. AE tests and DRA tests, etc.). Techniques are in various stages of development ranging from the proven / practical use stage to the research/development stage. However, limiting conditions are unavoidable for measurement and analysis, including a depth limit for application. Thus, during the reporting period, there was no highly reliable technique for cost-effective and efficient measurement of 3-D in situ stress at 1,000 m depth [(95)].

Because of this situation, the development of in situ stress measuring equipment for determination of in situ stress at depths up to 1,000 m was required. The equipment to measure in-situ stress by stress relief or strain recovery is based on the over-coring method (Figure 4.80).

Before proceeding with the development of this equipment, literature surveys were carried out on domestic and overseas studies. In 1996 and 1997 FY, recommended techniques and a conceptual design of the equipment were determined. Also, future tasks were determined. [(87,90,95)]. Based on the results, design of the measuring equipment and manufacturing of parts has been carried out since 1998 FY [(89)]. The parts are a strain gauge cell (with a thermometer), pressure vessel to house batteries, data recorder and an azimuth-inclination measuring device [(89)]. The latter components, the azimuth-inclination measuring device and the data recorder, will be manufactured and their function tests will be carried out in and after 2000 FY.



(a) Details of probe



(b) Procedure to measure in-situ stress

Figure 4.80 3-D in-situ stress measurement equipment for depths of up to 1,000 m

4.5.6 Techniques and equipment for use in Phases II and III

4.5.6.1 Continuous-wave radar investigation techniques

Radar tomography can be used for two boreholes with separations of up to several tens of meters. It is presumably possible to expand the distance by employing continuous waves as transmitting-receiving signals, especially, in crystalline rocks such as granite characterized by a large resistivity and a small energy loss (attenuation). An improvement of the borehole radar investigation technique used in the Kamaishi Mine, the continuous wave radar investigation method is being developed. It aims to expand the survey depth and enhance resolution. In the long run, this development aims for higher space resolution and longer survey distance than the current radar capabilities, by putting the ACROSS (accurate regulation of steady signal system) technology [(96)] to practical use.

In 1998 FY, an experimental device of continuous wave radar was manufactured. In 1999 FY, with the purpose of understanding the heterogeneity near the ground surface and using this technique as a tool for understanding the frequency-dependence of ground electrical permittivity, the input impedance in air and on water were measured using three types of antennas with targeted frequency bands: 1 to 5, 5 to 50, 50 to 200 MHz. As a result, basic data on the resultant impedance of antenna and medium was obtained [(88)].

4.5.6.2 A long-term monitoring system using boreholes

The MP system described above for observing groundwater pressures does not have the measuring capability to function under a high differential pressure environment that may be caused by shaft excavation in the Phase II and during a large-scale pumping test. Consequently, a long-term monitoring system is being developed to cope with high differential pressure conditions.

Application tests were carried out to 200 m depth using the system manufactured in 1999 FY. As a result, its overall function was ascertained. However, noise (chattering) occurred in the depth sensor, which hindered connection with measuring ports at the correct depths. Oil fouling inside the casing was determined to be the main cause. Cleaning the inner surface of casing with organic solvent solved the problem [(88)].

4.5.6.3 An investigation system of research gallery walls

The walls of research galleries will be mapped during excavation. The information obtained by the observations will be important to assess the predictions made in Phase I and to understand the geological environments around the research gallery. So far, engineering information on shaft and tunnel face surveying systems has been gathered and the following future tasks determined [(89)].

· It is important to determine the distribution of discontinuities (e.g. fractures), water inflow conditions and weathering. Determination of fractures requires a high signal / image resolution, whereas extraction of water inflow and weathering requires color capability. Thus, a survey system employing a digital camera was thought to be appropriate.

· When the wall of a 6m-diameter shaft is covered by 4 to 6 photographs using a digital camera, with the highest resolution (six million pixels as of 1998 FY), resolutions as small as some 2mm can be expected.

· Design and cost of the investigation system depend largely on a degree of automation of the photography using digital cameras.

· Extraction of discontinuity planes by image processing was put to practical use. However, automatic extraction of water inflow conditions and weathering has yet to be tested with a practical example.

4.5.7 Data base construction and development of a data analysis/visualization system on geological environments

4.5.7.1 Data base management and construction

The MIU Project will produce a huge amount of data from the investigations. Introduction of database management systems began in 1996 FY for management and utilization of the data (90). One of them is GEOBASE, an integrated underground resources data base system developed by Geothermal Technology Development Co., which is being improved as follows (87,89).

· Addition of a table for information management to guarantee the data quality, including data acquisition and analysis techniques

· Addition of a table for the management of core descriptions in boreholes and chemical analyses

· Addition of a table for time management of data from boreholes

· Addition of a function to refer to and display the information extracted by BTV investigations

· Development of a PC-based simple reference software

· System innovation so that GEOBASE can be accessible to every researcher using intranet.

The location of boreholes, geophysical logging, hydraulic tests, geological columnar sections and surface water hydrology would be registered in the data base system.

4.5.7.2 Data analysis/visualization system of geological environments

Geological models form the basis of the models for hydrology, hydrochemistry and rock mechanics. Thus, 3-D visualization of the geological model through computer graphics makes it easy to share the necessary information for constructing the other models.

EarthVision, 3-D visualization software developed by Dynamic Graphics Inc., has been used for visualizing the geological model. The software forms a 3-D geological model by estimating shapes of discontinuity planes such as boundaries between geological formations and faults, and integrating the discontinuities by considering their relationships with respect to relative positions and development processes (16,17).. Furthermore, this software has had demonstrated application in overseas projects for geological disposal, such as at Sellafield (Nirex), Wellenberg (Nagra), Äspö HRL (SKB) and Yucca Mountain (USGS, USDOE) (18). This system was used for the construction of the geological model in the Phase I-a in the MIU Project (See Section 4.1). Minimum tension theory based on spline interpolation, one of the functions of

EarthVision, was applied to estimate the ground surface, geological boundaries and fault planes. The method is an interpolation between adjacent data to find the smoothest curved surface by an n-dimensional polynomial formula using the input data of positions and directions [19].

In addition, this visualization system ensures a close connection with the above-mentioned data management system, GEOBASE and also introduces FRAC-AFFINITY [17], a 3-D saturated/unsaturated seepage flow analysis code using a finite difference method. FRAC-AFFINITY has the following characteristics.

- It can model a hybrid medium that allows simultaneous handling of a porous medium and a fractured medium.
- The fractured medium component can handle both deterministic fractures and stochastically generated fractures.
- Physical properties in a porous medium and a fractured medium (deterministic) can be set either homogeneously for every geological formation/ structure or heterogeneously using statistical techniques based on fractal theory.
- The fractured medium part (stochastically generated) can be set to develop either at random or at fixed positions. Physical properties can be set to develop either homogeneously or stochastically based on a normal distribution.
- Data-interface environments from EarthVision used for the construction of geological models are already systematized. Therefore, it was easy to form input data and differential meshes.

Improvements are expected in and after 2000 FY. For example, a function to take anisotropic permeability of fractures into consideration was expected to be added to the saturated/unsaturated seepage flow analysis code in the existing systems.

4.5.8 Techniques and equipment for information disclosure

4.5.8.1 Virtual reality technology

In order to explain geoscientific studies carried out in the MIU Project to the general public more effectively, virtual reality (VR) technology has been investigated. Also, its applicability to the MIU Project was examined. Specifically, new software has been developed. This software enables users to feel as if they are walking around in the underground facilities; a realistic experience is provided by using a head mounted display (HMD) [97]. In addition, scale models [87] for explaining the MIU Project and the drilling techniques employed are on display in the community plaza at the Shobasama Site.