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Recent Technical Developments in PLAD Method

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Abstract:

The technical details, features, and scope of application of the pipeline arch drill (PLAD) method developed for installing pipelines at the crossings of rivers, harbors and other obstructions are described. Water jet drilling and rock formation drilling technologies developed recently are introduced. The water jet drilling device, which has excellent durability and high drill path control efficiency, was designed to replace the conventional hydraulic downhole drilling motor. After various tests, it was successfully applied in a pipeline crossing at the mouth of the Tenpaku River in the Nagoya Harbor. The rock formation drilling technology, after study of the tool configuration and drilling procedure, was applied with satisfactory results to the drilling of slant boreholes through a rock formation composed of sand and rock layers in the project of a pipeline crossing at the Onga River, Ashiya Town, Fukuoka Prefecture. Data for future research were collected in the way.

1. Introduction

The PLAD (pipeline arch drill) method, a horizontal directional drilling method for pipeline crossings, drills from the surface of the ground an arched hole along a designed directional path beneath obstructions and installs a pipeline through the drilled hole.

At the end of 1977, Nippon Steel Corporation initiated work on the development of the PLAD method along the line of directionally controlled drilling techniques, that are employed in oil well drilling, with a view to establishing a tunneling-by-jacking method requiring no shafts. The PLAD method was tested for validation in the Kanto loam ground layer in 1979, followed by several field experiments until 1981. In 1982, Nippon Steel made a technical tie-up with Reading & Bates Construction Co. of the United States that had a similar drilling method.

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While oil well drilling digs a vertical shaft to a deep layer, the PLAD method drills a horizontal hole in the surface layer. Being a pipeline installation method, the PLAD method must also ensure high directional accuracy at the exit point.

The PLAD method was employed in an actual installation project for the first time in 1979. After know-how accumulation and technical improvement through many projects thereafter, the PLAD method has expanded its application range and has aggregated a drilling length of 15,449 m in 24 projects.

In this report, the PLAD method is outlined first, followed by descriptions of newly developed water jet drilling and rock formation drilling techniques.

2. Description of PLAD Method

2.1 Drilling procedure

The PLAD method is a three-step mechanized micro-tunneling method whereby a hole is drilled by a drilling equipment installed on the ground. **Fig. 1** shows the procedure.

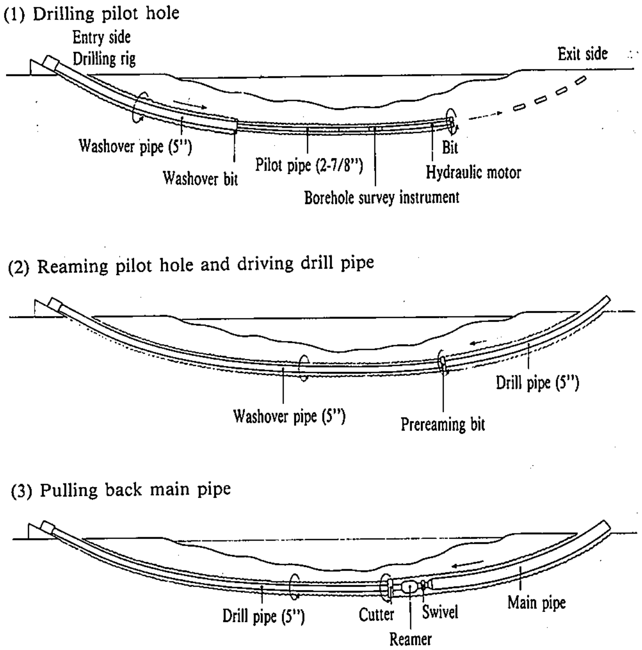

Fig. 1 Standard procedure by PLAD method

(1) Drilling pilot hole

Using a special drilling equipment called a drilling rig, a 2-7/8 inch pilot pipe is driven along the design path, and a pilot hole is drilled by a drilling device attached at the end of the pilot pipe and provided with a path control function. The actual path of the pilot hole is monitored from the surface with a borehole survey apparatus located right behind the drilling device.

As the pilot pipe is driven over an increasing length, a load around the pilot pipe increases. Each time the pilot pipe has been driven for a certain distance, a 5-inch washover pipe is driven rotating concentrically over the pilot pipe so as to reduce the latter's load and allow it to follow the design drill path.

When the pilot pipe has reached the exit point, the washover pipe is also driven to the exit point, and then the pilot pipe is removed.

(2) Prereaming pilot hole and replacing drill pipe

A drill pipe of the same 5-inch diameter and strong enough to pull back the main pipe is connected through a prereaming and hole-opening bit to the washover pipe that has reached the exit point, by rotating and moving the drill pipe toward the drilling rig, prereams the pilot hole, and replaces the washover pipe. This step may be omitted depending on the drill length, pipe diameter and soil conditions.

(3) Pulling back main pipe

A fly cutter and a barrel reamer are attached to the leading end of the drill pipe at the exit point and connected through a swivel joint to the pulling header at the leading end of the main pipe (see **Fig. 2**). As the drill pipe is rotated with this arrangement, the hole is enlarged by the fly cutter and shaped by the barrel reamer, and the main pipe is pulled unrotating through the hole toward the drilling machine and is installed in place.

Any interruptions in the operation of pulling the main pipe back because of welding and other operations must be minimized to prevent the restraining force of the surrounding soil from increasing. Space permitting, it is desirable that the pipeline be prefabricated into a single length by welding prior to the pulling-back operation through the drilled hole.

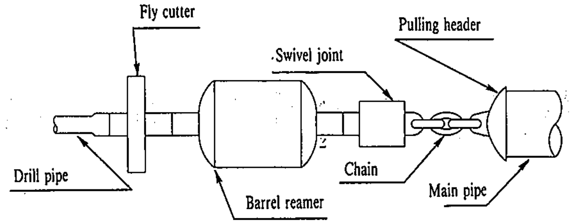

Fig. 2 Construction of pullback mechanism

2.2 Features of PLAD method

The PLAD method features the following:

(1) It can drill a long hole from 800 to 1,500 m in one operation without intermediate shafts or interim jacking devices.

(2) It can drill a hole to any desired depth without constructing vertical shafts that are indispensable with conventional methods. The absence of shaft work adds to the safety and ease of operation.

(3) It does not require such supplementary work as wellpoint insertion and chemical grouting, nor does it involve the risk of ground subsidence, subterranean water exhaustion and contamination. It thus incurs a minimum environmental disruption.

(4) It can maintain the drill path direction with high accuracy by its own drilling-controlling and readjusting mechanism and by a borehole surveying and steering system.

(5) It does not require shaft construction or supplementary work, resulting in a substantial shortening of the construction period.

(6) It can reduce the construction cost by shortening the construction period, eliminating the needs for segments to prevent caving-in and auxiliary jobs, and preventing the problem of compensation for environmental pollution.

2.3 Path drilling techniques

(1) Structure of Drilling device

The pilot hole drilling device consists of a drilling bit, a bent housing, and a hydraulic motor, as shown in **Fig. 3**.

The hydraulic motor consists of a cylindrical pipe called stator with a spiral rotor inside. The mud flows in the gap between the stator and the rotor and produces the rotating torque for the pilot hole drilling device. Transmitted from the surface through the drill pipe, the mud drives the hydraulic motor, which accordingly rotates the drilling bit at higher speed, leaves the end of the drilling bit, and returns together with the drill cuttings through the gap between the pipe and the walls of the pilot hole to the surface.

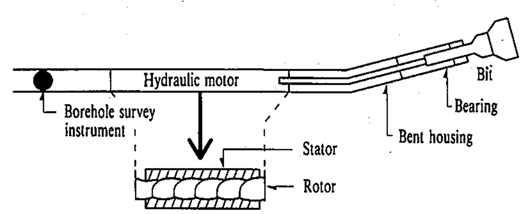

Fig. 3 Pilot hole drilling mechanism

(2) Path directional control

The pilot hole drill path is controlled by rotating only the leading drill bit with the hydraulic motor, keeping the pilot pipe from rotating, and controlling the direction of the bent section called a bent housing.

The principle of directional control is as illustrated in **Fig. 4**. When the pilot pipe is thrusted by the drilling rig, the front part of the bent housing produces a bending moment under the reaction of surrounding soil, and the leading end of the pilot pipe creates a steering bias in the bend direction. The drill path of the pilot hole can thus be controlled in any desired direction. The pilot hole directional control is performed by changing the magnitude of the bending moment while adjusting the drilling rate or mud flow rate.

(3) Functions of mud

The blending of the mud,or the drilling fluid, used in the PLAD method depends on the quality of soil and water to be encountered. Basically, water, viscosity-increasing agent surfactant and the like are added to bentonite and agitated to produce the mud.

The mud plays such extremely important roles in the PLAD method as: 1) driving the hydraulic motor; 2) cooling the drilling bit; 3) removing the cuttings; 4) preventing the borehole from caving-in; and 5) lubricating the pilot pipe.

After the mud is used, it is recovered to the surface, removed of the cuttings, adjusted as to specific gravity, viscosity and other properties, and reused as drilling fluid.

2.4 Main items of equipment

(1) Drilling equipment

The drilling equipment consists of an inclined reaction rack and hydraulically powered-thrusting, rotating and tracting devices, and is fixed to an anchor installed at the entry point.

The drilling equipment provides driving force when the pilot pipe is driven, both rotating and driving forces when the washover pipe is driven, and both rotating and tracting forces when prereaming the pilot hole or replacing the drill pipes, or pulling the main pipe. The PLAD method is technically unique in that a complete set of operations from the driving of the pilot pipe with low speed and small thrust to the retraction of the main pipe with high speed and large force can be controlled by a single machine.

At present, there are two drilling rigs, PLAD-250 and PLAD-300 (see **Photo 1**).

(2) Bentonite mud slurry plant

The bentonite mud slurry plant consists of hoppers for bentonite, mixers and other mud preparing devices, and tanks, mud-feeding pumps and other mud reconditioning devices.

Since the mud amount to be used differs from, step to step of installation, multiple feed pumps are installed, and operated as required to meet the total amount of mud. A mud reconditioning device has screens to remove solids from the return mud.

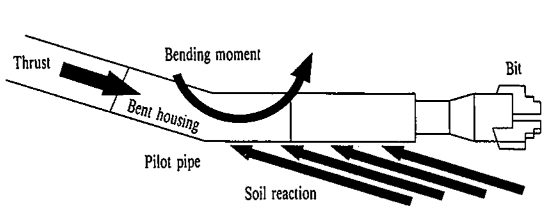

Fig. 4 Principle of directional control

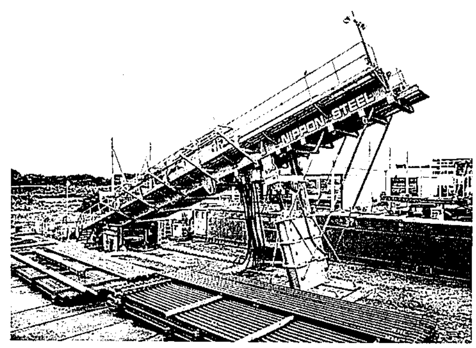

Photo 1 Drilling Rig PLAD-300

(3) Control box

The control box houses operation control panels for the drilling rigs and mud feeding pumps, instrument panels for thrust, torque, and mud pressure and flow rate, and a direction-controlling computer. These devices allow all the necessary information to be integrated and the horizontal directional drilling operation to be performed properly and efficiently.

2.5 Direction-controlling system

(1) Borehole survey instrument

The borehole survey instrument used to detect the position of the pilot hole drilling path consists of 1) instruments such as compass, clinometer, and so on, 2) downhole unit composing of converter, battery and transmitter, and 3) uphole unit including receiver, data processor and so on. Forming a circuit through the ground and the earth conductor allows measuring the inclination and azimuth of the drill head efficiently without cable.

Theses sensors are stored in a non-magnetic collar of stainless steel located immediately after the hydraulic motor to protect them from the adverse effect of magnetism of the pilot pipe.

(2) Directional control

Changes in the driving, transverse and depth directions near the leading end of the pilot pipe are calculated from measured changes in the azimuth and inclination of the pilot hole, and are then integrated over the length of the pilot pipe to calculate the coordinates of the drill path. The calculated drill path coordinates are compared with the designed drill path coordinates, the difference between those two coordinates are checked to see if they fall within allowable limits. If necessary, corrective drilling is made to follow the specified drill path with close tolerances.

The directional accuracy of the pilot pipe at the exit point can be enhanced by locating the induced magnetic field position of the pilot pipe through vertical boreholes drilled near the exit point.

2.6 Scope of application

(1) Sites of application

Main applicable sites of the PLAD method are listed below with brief descriptions of its advantages:

(i) River, harbor and other water channel crossings

The PLAD method minimizes the effects of installation on banks and revetments, does not cause water contamination or subterranean water exhaustion, nor has it any impact on navigation.

(ii) Road, railroad and other vehicle traffic crossings

The PLAD method does not cause the stoppage of road and railroad traffic. Being a drilling method for holes 1,000 mm or less in diameter, it is not liable to cause any ground elevation or subsidence.

(iii) Shore approach of submarine pipeline

Involving no open excavation, the PLAD method can conserve the natural coastline, posing no such problem as compensation for fishermen in the affected coast. It also ensures easy connection with submarine pipelines that are installed by trenching and backfilling.

(2) Scale of construction

The PLAD method is suited for installation of small-diameter pipelines over a long distance. The maximum diameter of pipe that can be installed with existing PLAD facilities is 1,000 mm. Although the maximum length that can be drilled by the PLAD method varies with soil conditions, it is generally 1,500 m for 300-mm diameter pipe and 800 m for 1,000-mm diameter pipe.

(3) Soil conditions

The soil best suited for tunneling and jacking by the PLAD method is homogeneous cohesive clay, followed by sandy soil. The method can accommodate a stratum change if it comprises alternating layers of cohesive clay and sandy soil. The method can also be applied to gravely sand layers of certain gravel size and gravel mixture ratio, and to soft rock layers. Recently, it has also been successfully employed at a composite lamellar ground site containing a hard rock layer in part.

3. Development of Water Jet Drilling Technique

3.1 Purpose of development

Traditionally, pilot holes are drilled by driving the hydraulic motor shown in **Fig. 3** and rotating the drill bit by the torque developed by the motor.

The hydraulic motor is liable to wear and breakage and reaches the end of its service life after 200 to 500 m of drilling. It must therefore be changed two to five times for drilling 1,000 m, resulting in lowering the construction efficiency. Bringing the measuring position as close as possible to the drilling point is important in efficiently controlling the direction of the drill path. There are no Japanese manufacturers who make hydraulic motors for horizontal directional drilling. When a hydraulic motor fails, it would be difficult to repair it quickly. This situation calls for the domestic fabrication of horizontal directional drilling devices.

As an alternative drilling technique for the conventional hydraulic motor drilling technique, application of a water jet, conventionally used for stabilizing soft soils, was studied. The study led to the development of the water jet drilling mechanism shown in **Fig. 5**.

3.2 Study and experiment

3.2.1 Description of study

To study the applicability of the water jet technique to the PLAD method, experiments were made, comprising water jetting in air and water jet cutting in soft soils with SPT (Standard Penetration Test) N-values of 20 to 50 using existing pump equipment. These experiments used three original types of leading end tools fabricated by changing the length and angle of the bent rod, as shown in **Fig. 6**.

While the drilling rate and mud flow rate were kept constant, three items of drilling condition, namely, curved path drilling, wear near the nozzle, and the water jet pressure and velocity were studied. **Photo 2** shows water jet cutting under way.

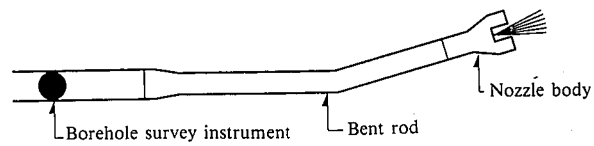

Fig. 5 Structure of water jet cutting device

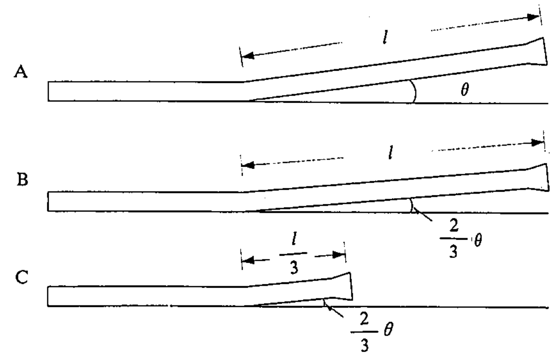

Fig. 6 Geometry of water jet cutting tool

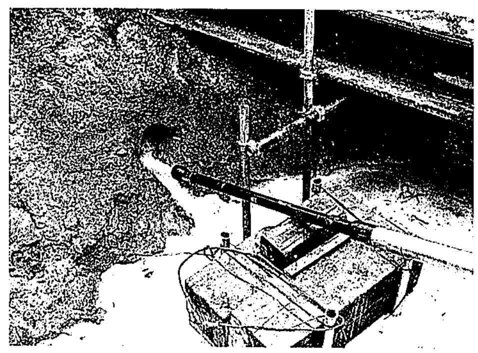

Photo 2 Water jet cutting under way

3.2.2 Experimental results

The following findings were obtained from the experiments:

(1) The radius of curvature obtained under the drilling conditions is 80 to 150 m for tool A, 150 to 500 m for tool B, and 500 to 1,200 m for tool C. The effects of the length and angle of the bent portion were thus qualitatively confirmed.

(2) The amount of wear near the nozzle is so small that there seems to be no need for changing the tool during one drilling operation.

(3) The relationship between the mud velocity and pressure in air was clarified. At the same time, it was confirmed that the mud pressure during drilling under-ground can be raised by a maximum of 1.3 times the mud pressure in air. The considerations to be given in setting the water jet cutting conditions were thus clarified.

The experiments verified the full capability of water jet cutting by the use of existing pump equipment.

3.3 Application to Tenpaku River mouth crossing

According to the results of desktop study and drilling experiment, the water jet cutting technique was applied to the installation of a 600-mm diameter high-pressure gas pipeline beneath the mouth of the Tenpaku River in the Nagoya Harbor. As shown in **Fig. 7**, the pilot hole was drilled first downward with a 600-m

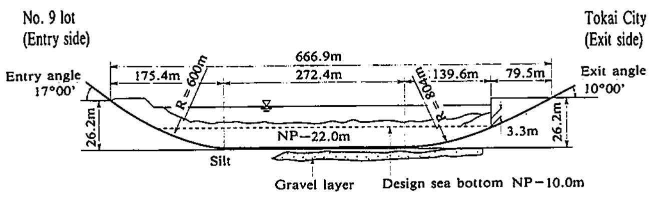

Fig. 7 Cross section of Tenpaku River mouth crossing, Nagoya Harbor

radius of curvature from the entry point, then horizontally, and finally upward with a 804-m radius of curvature toward the exit point. The total length drilled was 672 m. The soil was a practically uniform silty soft soil with SPT N-values of 10 or less. The length of the cutting device structure was about one-third of that of the conventional hydraulic motor drilling mechanism.

The benefits of water jet cutting as confirmed in this project are as follows:

(1) The drill path can be achieved in soft grounds with the same accuracy as done with the hydraulic motor.
(2) There is little wear near the nozzle, and a total length of over 700 m can be drilled without changing tools.
(3) Constant mud pressure and flow rate assure freedom from instrument damages and battery exhaustion.
(4) Drilling can be performed with greater stability than with the hydraulic motor, depending on soil conditions.

3.4 Future issues of water jet cutting

To expand the scope of application of water jet cutting and establish it as a stable drilling technique, the following data will be gathered and studied through actual projects:

(1) Verification of applicability to various grounds
(2) Establishment of drilling control method
(3) Selection of optimum tool geometry
(4) Study on the feasibility of drilling in hard soils and clays with high SPT N-value by using higher mud pressure

4. Development of Rock Drilling Technique

4.1 Technical issues

Application of the PLAD method to rock drilling involved the following issues:

Issue 1: Rock drilling calls for full thought paid to the establishment of the drill path for reasons 1) the force to which the bent rod of the drill bit is subjected in the rock and the scope over which the curved path can be controlled are not known; and 2) there are no reliable methods to correct the path of the drilled hole.

Issue 2: Unlike the sand and clay layers that can be drilled while disturbing them by the rotating force of the drill bit and by the mud pressure, the rock formation requires that the bit be pushed hard to drill a hole in it with enough torque under pressure. The drilling tool configuration and drilling procedure must be reviewed accordingly.

Issue 3: The drill cuttings are removed by the mud through the gap between the hole wall and the drill string. Unless the drill cuttings are completely removed, they may build up in the pilot hole to increase the resistance against the drilling operation because the wall of the pilot hole is stable. The mud properties and flow rate must be adequately set for the thorough removal of drill cuttings from the pilot hole.

Described below is the drilling method adopted in an actual project which was carried out through a complex ground where rock formations outcropped a sand layer.

4.2 Drilling procedure and tool configuration

4.2.1 Establishment of drill path

Fig. 8 shows the soil conditions and drill path profile of an Onga River crossing project in Ashiya Town, Onga County, Fukuoka Prefecture. The project involved the installation of a sewer pipeline with a main nominal diameter of 300A (304.8 mm for the contractor) and casing pipe nominal diameter of 350A (355.6 mm for the contractor). A rock layer with an uniaxial compressive strength of 1,000 kgf/cm^2 was present over about 77 m of the total length of 310 m on the right bank side. Since drilling a curved path in the rock involved many uncertain factors, it was decided to drill a straight slant path in the first rock layer and to drill a curved path in the remaining sand layer to the exit point by the conventional direction-controlled drilling method.

4.2.2 Determination of drilling steps

(1) Drilling pilot hole

Although it was possible to drill the pilot hole from either the rock layer side or sand layer side, it was decided to start drilling it from the rock layer side giving consideration to such factors as 1) supply of sufficient mud pressure to the bit; 2) prevention of buckling of the drill pipe due to path changes in the sand layer; and 3) reduction in bit change time and assurance of the desired path.

(2) Reaming schedule

Two methods were available for reaming the pilot hole. The first method involved drilling the pilot hole in the sand layer after the completion of pilot hole drilling in the rock layer and pulling back the pipeline through the completed pilot hole from the exit side. The second method involved first prereaming the pilot hole in the rock layer to the desired diameter by thrusting and then drilling and reaming the pilot hole in the sand layer. Since the pullback method had such problems as 1) collapse of the pilot hole in the sand layer during the reaming of the pilot hole in the rock layer; 2) unsuitability of rock pilot hole reaming tools for reaming the pilot hole in the sand layer, it was decided to ream the pilot hole by thrusting from the entry side.

The reaming schedule was based on a standard schedule for oil wells and was established as shown below to prevent the incomplete removal of drill cuttings and the occurrence of drilling troubles.

- Pilot hole drilling: 12-1/4" bit, 8" hydraulic motor, and 9-5/8" casing pipe
- First-stage prereaming: 17-1/2" hole opener and 13-3/8" casing pipe

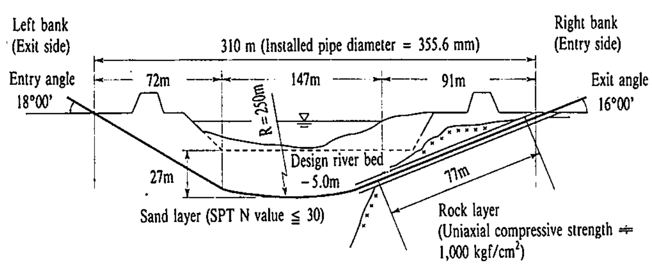

Fig. 8 Profile of Onga River crossing project, Ashiya Town, Onga County, Fukuoka Prefecture

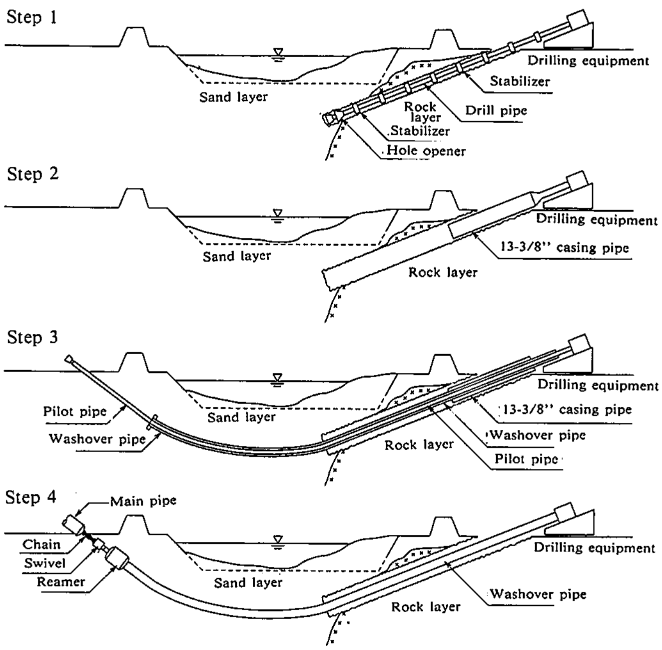

Fig. 9 Drilling steps

- Second-stage reaming: 20" hole opener and 13-3/8" casing pipe

The drilling steps thus determined are shown in **Fig. 9**.

4.2.3 Rock drilling tools and drill pipe configuration

A tip-inserted roller tricorn bit having excellent wear resistance and durability and capable of accommodating a wide variety of soils was adopted as the drill bit.

The required drilling torque and thrust were calculated by the following equation, an empirically modified version of an equation proposed by Hughes Tool Co. of the United States:

$$T = 2.96 \times 10^{-2} \cdot k \cdot W_d^{1.5} \cdot D^{2.5} + 0.7D$$

where T is required drilling torque (kg·m); k is soil coefficient; W_d is load per unit bit diameter (kg/cm); and D is size of bit diameter (cm).

The drilling rate was calculated by the following equation, an empirical equation of the Public Works Research Institute, Ministry of Construction, with an efficiency of 0.7 taken into account:

$$R = 0.11568 \cdot 0.7 \cdot N \cdot W_d / q_u$$

where R is drilling rate (m/h); N is bit rotation number (rpm); and q_u is uniaxial compressive strength of soil (kgf/cm^2).

The drill tool and pipe specifications were determined from these results as well as the resistance to which the drill string would be subjected.

The 8"-size hydraulic motor adopted was capable of delivering the necessary torque and thrust and controlling direction, was not easily drooping under gravity, was lightweight, and was fit with an angle adjusting device. Casing pipe of a special thread specification was adopted as the pipe to transmit the thrust and torque to the bit for reasons of 1) high stiffness for force transmission; 2) low likelihood of drooping; 3) light weight and ease of engagement and disengagement; and 4) sufficiently large diameter for efficient removal of drill cuttings. A guided hole opener used in oil well drilling was adopted as reaming tool for reasons of 1) drilling speed; 2) necessary torque; and 3) versatility.

On the basis of the above study results, it was decided to drill the pilot hole with the tool combinations shown in **Fig. 10**. Rock drilling tools are shown in **Photo 3**.

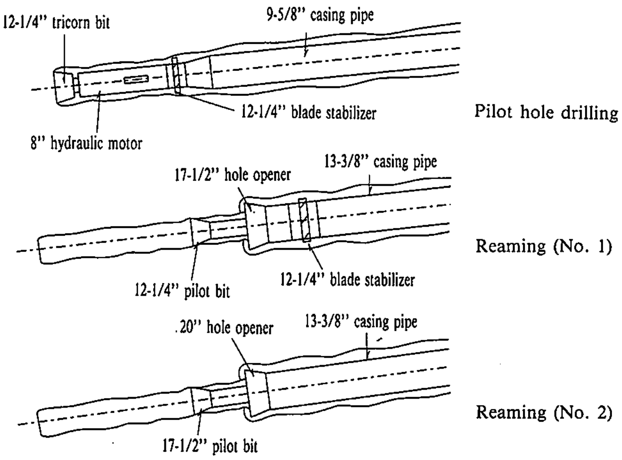

Fig. 10 Rock drilling tool combinations

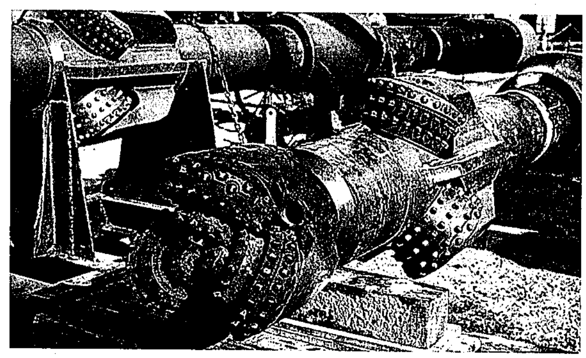

Photo 3 Rock drilling tools

4.2.4 Discharge of drill cuttings

To numerically validate the ability of the mud to transport the drill cuttings, the necessary mud velocity and properties were determined according to the following equation and conducting laboratory experiment simulating the transport of drill cuttings through a slant hole:

$$V_{si} = \sqrt{\{4 \cdot d \cdot g(\varrho^1 - \varrho)/3 \cdot \varrho \cdot C\}} \cdot \sin\theta \cdot C_{in}$$

where V_{si} is slip velocity (cm/s); d is size of cuttings in diameter (cm); g is gravitational acceleration (980 cm/s^2); ϱ^1 is unit volume weight of cuttings (g/cm^3); ϱ is unit volume weight of mud (g/cm^3); C is coefficient of friction; θ is angle of inclination (°); and C_{in} is correction factor.

4.3 Future issues

The drilling project was carried out on the basis of the study results described above. The work was completed with almost the same drilling rate as planned, and basic data for path control were obtained. Techniques for drilling curved paths in rock formations, including the method of path steering, will be established in the near future.

5. Conclusions

The technical outline and recent progress of the PLAD method have been described above.

The PLAD method is not only unique, but is greatly beneficial, depending on how it is applied. As a method of installing pipelines without excavation, the PLAD method is employed in such fields as gas, oil, water, sewage, electricity, and communications.

Amid the advancement of infrastructure toward the 21st century, the need for non-excavation tunnelling methods is expected to mount. The authors intend to further develop the PLAD method, expand its scope of application through its practical application to many installation projects that vary widely in terms of project scale, ground conditions and operating conditions, so that it may grow into a mainstay process for various lifeline installations.

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