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Development of Jumbo-Pipe Line Arch Drill (J-PLAD) Method

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Abstract:

Since 1993, Nippon Steel has developed a new non-open-cut microtunneling method (designated the J-PLAD method) based on the pipe line arch drill (PLAD) method that has been used to install many pipelines crossing rivers and harbors. The J-PLAD method and an actual-scale field experiment conducted in 1994 are described. The field experiment verified the viability of the entire J-PLAD system from the drilling of a pilot hole through the removal of drillings to the installation of a main pipe. It also yielded construction expertise, and confirmed that arch tunnels with a diameter of up to 2,000 mm could be constructed by the J-PLAD method.

1. Introduction

The pipe line arch drill (PLAD) method, an application of a method for drilling curved boreholes in the oil industry, involves boring at an angle from the surface of the ground, then drilling the hole along a gently curved path beneath an obstruction such as a river or harbor to the opposite side. The pipeline is laid in the drilled and reamed hole. The PLAD method features the following:

(1) Holes up to 1,500 m in length can be drilled in one operation.
(2) Holes can be drilled entirely from the ground surface. The absence of work in shafts and pipelines assures a safe working environment .
(3) Supplementary tasks such as well point insertion and dredging, are unnecessary therefore there is no risk of ground subsidence, underground water supply exhaustion, and river and sea water pollution.
(4) Shaft construction is not requiered, resulting in the completion of a pipeline in a shorter time at a lower cost compared with conventional methods.

About 15 years have passed since the PLAD method was first applied in an actual project. Accumulation of construction expertise and implementation of technical improvements during the intervening period have expanded the applicable scope of the PLAD method and have led to the usage of the PLAD method in 27 projects to date. The microtunnels built with the PLAD method range from 50 to 1,000 mm in size and from 40 to 1,380 m in length. As shown in **Fig. 1**, the installation capability of the

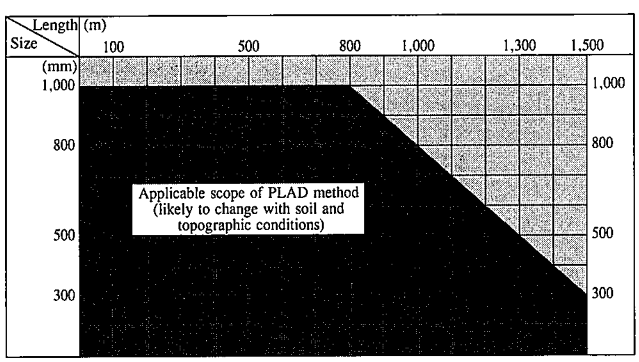

Fig. 1 Size and length of tunnels that can be driven by PLAD method

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PLAD method has steadily been increased for small- and medium-diameter pipelines to a pipe diameter of 1,000 mm and a total length of 1,500 m.

To meet the need for larger microtunnels, in 1993 Nippon Steel Corporation started developing the Jumbo-PLAD method (J-PLAD method) whereby microtunnels up to 2,000 mm in size and 1,500 m in length can be bored.

In this report, the conventional PLAD method and the new J-PLAD method are outlined, followed by the description of the field experiment conducted in 1994 and its results.

2. Description of J-PLAD Method

2.1 Mechanism

2.1.1 Conventional PLAD method

The basic construction procedure of the conventional PLAD method consists of three stages: 1. drilling a pilot hole; 2. reaming the pilot hole and replacing the drill pipe; and 3. pulling back the main pipe. In the main pipe pulling-back stage, a cutter and a reamer are attached to the leading end of the drill pipe on the reception side on the ground surface, and the main pipe is connected through a swivel to the reamer, as shown in **Fig. 2**. As the drill pipe is rotated with this arrangement, the hole is enlarged by the cutter and shaped by the reamer, and the main pipe is pulled toward the launch side. The swivel joint prevents the main pipe from rotating during this procedure.

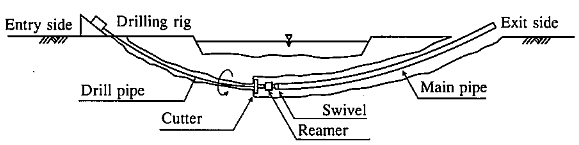

Fig. 2 Pulling back main pipe

2.1.2 Hole drilling and pulling back main pipe

In the main pipe pulling-back stage of the conventional PLAD method, the rotating force T of the cutter, main pipe pulling-back resisting force f_1 at the front of the cutter, and the main pipe circumferential frictional force f_2 all act on the drill pipe at the same time. If the size of the main pipe to be pulled back is to be increased with the tool arrangement of the conventional PLAD method, the three forces T, f_1, and f_2 will all increase, exerting an extremely large combined load on the drill pipe.

To disperse the drilling forces T, f_1, and f_2, the new J-PLAD method has an internal cutter drive motor and slide jacks installed in the dedicated drilling head as shown in **Fig. 3**.

The procedure for drilling the hole and pulling back the main pipe through the hole is as follows. While the cutter is rotated by the internal motor, the dedicated drilling head is pulled back toward the entry side by one stroke of the jack (during the drilling stage). After the cutter has stopped rotating, the trailing main pipe is pulled back one stroke by the jacks (in the pulling-back stage). The repetition of this series of movements allows the force f_1 alone to act on the drill pipe when the dedicated drilling head is pulled back and the force f_2 alone to act on the drill pipe when the main pipe is pulled back. As a result of this drill pipe load reduction, larger diameter main pipes can be pulled back and installed.

2.1.3 Removing drillings

The method of removing drillings in the conventional PLAD method is illustrated in **Fig. 3**. Mud is pressure fed from the entry side, discharged through the cutter, mixed with the drillings, passed through the gap between the main pipe and the surrounding soil, and flushed above the surface at the exit side. If this method is applied to the drilling of a larger hole, the

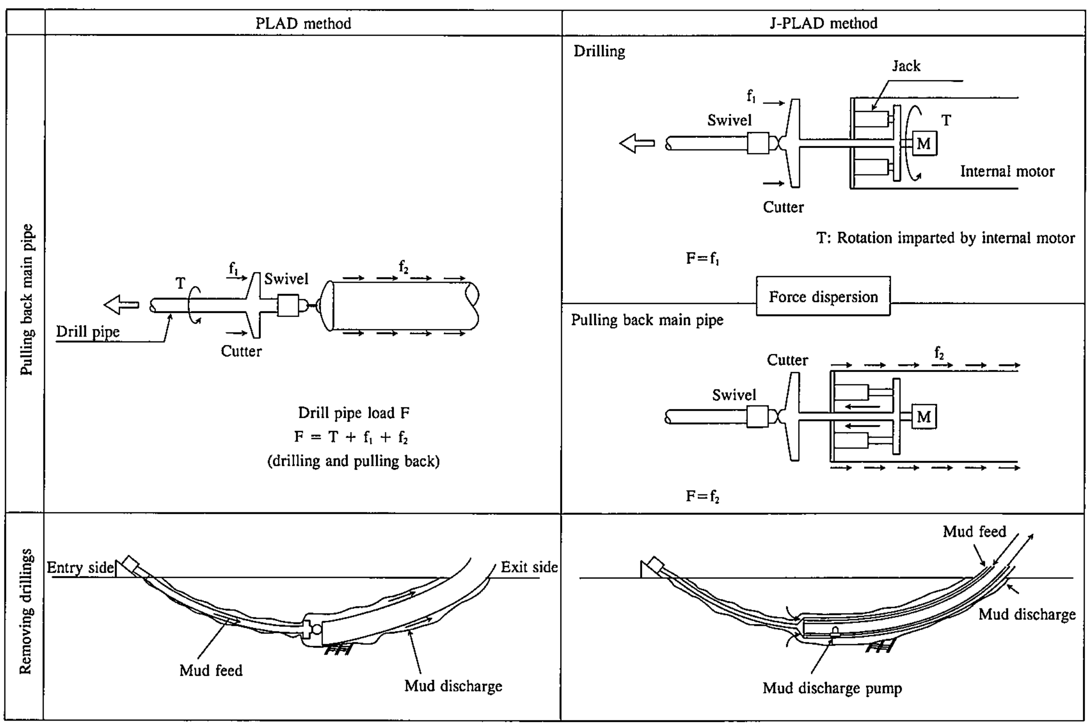

Fig. 3 Comparison of PLAD and J-PLAD methods in pulling back main pipe and removing drillings cuttings

increased amount of the drillings will not be completely removed and will constitute a large resistance on the pullback of the main pipe.

The J-PLAD method adopted the fluid transport method used in the mud shield method. Specifically, the mud fed from the exit side is mixed with the earth drilled at the front of the cutter and forced by a mud discharge pump out of the hole to the exit side. As a result, a larger volume of drillings can be consistently removed.

2.2 Drilling procedure

Similar to the conventional PLAD method, the new J-PLAD method consists of three basic stages as described below. **Fig. 4** shows the drilling procedure.

2.2.1 Stage 1: Drilling pilot hole

The drilling rig installed aslant at the entry side sets the 2-7/8-inch or 5-inch pilot pipe and drills a pilot hole along the designated path. The curved pilot hole is made by controlling the mud flow rate and the drilling rate with a mud pressure-driven or mud jet drilling device attached at the end of the pilot pipe that is provided with a guiding function. The actual path of the pilot hole is monitored from the ground surface with a borehole survey instrument located just behind the drilling device. As the pilot hole is bored over an increasing distance, the load acting on the pilot pipe increases. Each time the pilot pipe is bored over a certain distance, a 5-inch washover pipe (if the pilot pipe is 2-7/8 inches in size) is rotated concentrically over the pilot pipe to reduce the load of the pilot pipe and to guide the pilot pipe along the desired path.

2.2.2 Stage 2: Reaming 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 pilot hole reaming and drill pipe replacing bit to the washover pipe that has reached the exit side. Pulled back toward the entry side while being rotated, the 5-inch drill pipe reams the pilot hole and replaces the washover pipe. This stage may be omitted depending on the tunnel drilling length, pipe diameter, and soil conditions.

2.2.3 Stage 3: Tunnel construction

A dedicated drilling head is attached through a swivel joint and a universal joint to the leading end of the drill pipe at the exit side. The cutter is rotated by the rotary drive unit in the dedicated drilling head, the mud is discharged through the cutter, and the dedicated drilling head alone is pulled back toward the entry side. Then, the main pipe (trailing main pipe) is pulled back with the slide jacks (see **Fig. 5**). The reaction force developed when the dedicated drilling head and the tailing main pipe are pulled back is carried through the drill pipe to the drilling rig. The mud used for drilling the pilot hole is transported together with the drillings by the mud discharge pump through the pipe, treated at the mud plant at the surface of the ground, and recycled.

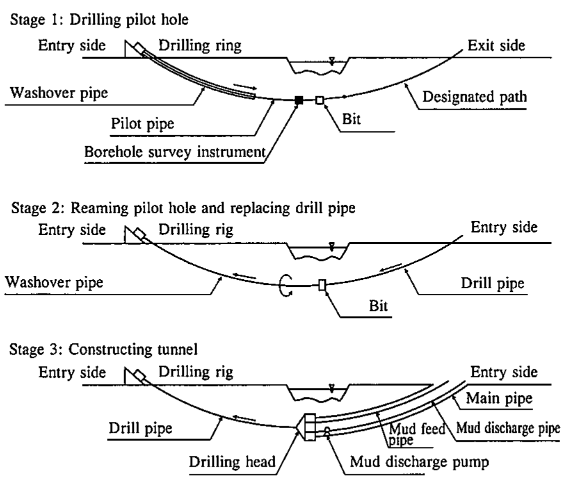

Fig. 4 J-PLAD method drilling procedure

2.3 Main items of equipment

2.3.1 Drilling rig

Anchored with H-shaped beams, the drilling rig is composed of an inclined reaction rack, and driving, rotating and pulling devices.

The drilling rig provides the driving force when the pilot pipe is being inserted, the rotating and driving forces when the washover pipe is being inserted, the rotating and pulling forces when the pilot hole is reamed and the drill pipe is replaced, and the pulling force when the tunnel is built. A technical feature of the J-PLAD method is that a series of operations from the insertion of the pilot pipe with low speed and small force to the construction of the tunnel with higher speed and larger force can be controlled by a single machine. The drilling rig is shown in **Photo 1**.

2.3.2 Mud recirculation plant

From the pilot hole drilling stage to the pilot hole reaming and drill pipe replacing stage, the mud plant consists of a hopper, mixer and other mud preparation devices, a tank, a mud feed pump, and recycled mud reconditioning equipment. The mud is supplied by the mud plant installed at the entry side.

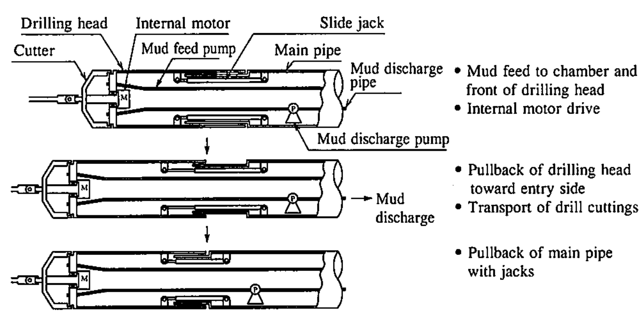

Fig. 5 Procedure for pulling back main pipe

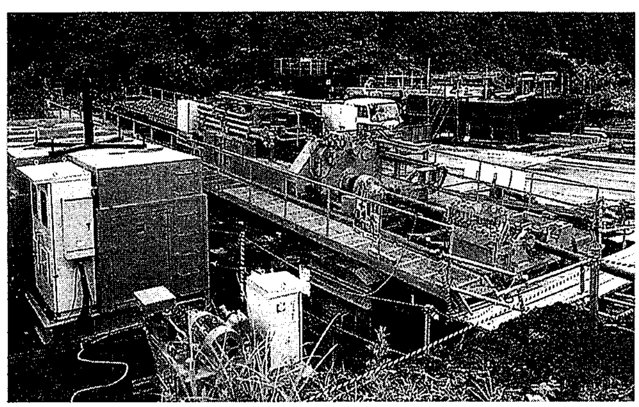

Photo 1 Drilling rig

The mud plant used in the tunnel construction stage consists of the mud feed pipe, jet pipe and mud discharge pump installed in the tunnel, in addition to the above-mentioned equipment installed at the ground surface on the exit side. As shown in **Fig. 6**, the mud is made in the hopper tank, temporarily stored in the suction tank, and fed by the mud feed pump through the feed pipe and jet pipe to the front of the dedicated drilling head. The mud discharge pump pumps the mud used in the drilling operation together with the drillings through the discharge pipe to the ground surface, where it is reconditioned and recycled.

2.3.3 Control boxes

Control boxes are installed on each of the entry and exit sides. The control box on the entry side houses control panels for the drilling rig and the mud feed and discharge pumps, instrument panels for adjusting the driving speed, force and torque, mud pressure and feed rate and other parameters, and drilling path direction control computers. This control box is used to control all necessary operations from the drilling of the pilot hole to the reaming of the pilot hole and the replacing of the drill pipe. The control box on the exit side is shown in **Photo 2**. It contains control panels for the dedicated drilling head, slide jacks, and mud feed and discharge pumps. The two control boxes are used in combination when constructing the tunnel.

2.3.4 Dedicated drilling head

As shown in **Fig. 7**, the dedicated drilling head contains the cutter in front and the cutter drive motor and trailing main pipe pullback slide jacks inside. It can bore tunnels up to 2,000 m long. The front of the cutter is equiped with mud jet nozzles and drilling bits.

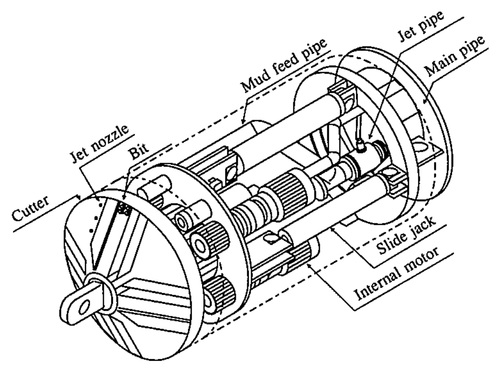

Fig. 7 Dedicated drilling rig

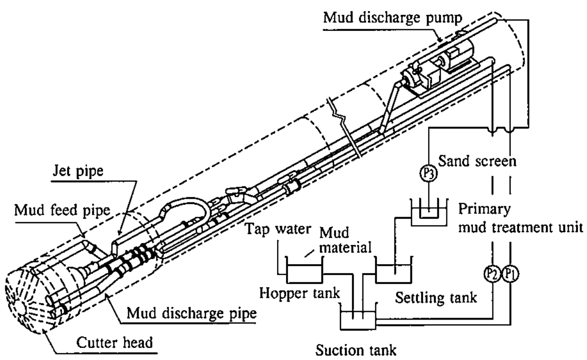

Fig. 6 Schematic of mud recirculation plant

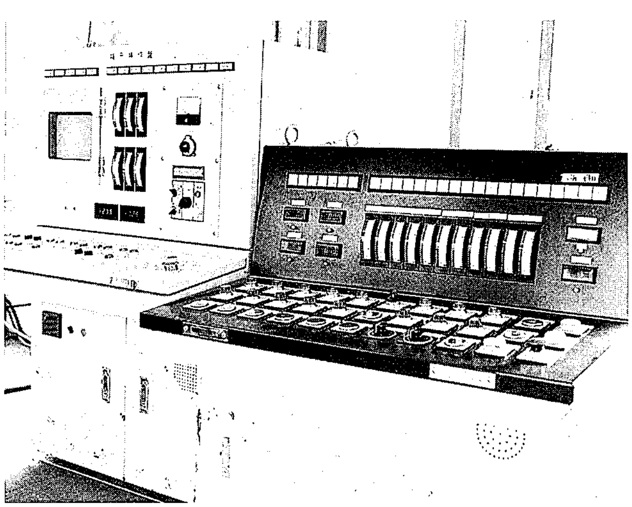
Photo 2 Control box at entry side

3. Field Experiment

The development of the J-PLAD method is aimed at building without using shafts an arch tunnel up to 2,000 m in length, at a speed two to three times faster than that of the shield tunnel method. From June to October, 1994, a field experiment was conducted using a full-scale drilling rig in Kisarazu, Chiba Prefecture, in order to verify the performance of the dedicated drilling head, the capacity of the mud recirculation system, and the drilling and pulling-back efficiency of the J-PLAD method.

3.1 Description of experiment

Since the land area available for the experiment was limited, the J-PLAD method was employed to bore a tunnel, 170 m long, 508 mm in diameter, and 1,500 m in the radius of curvature as shown in **Fig. 8**.

The procedure involved drilling a pilot hole with a 5-inch pilot pipe containing a mud jet drilling device, reaming the pilot hole, and replacing the drill pipe. Next, a swivel joint, a universal joint, and a 1,750-mm long dedicated drilling head were attached to the end of the drill pipe at the exit side. A 170-m long and 1,524-mm diameter pipe was then connected and pulled back through the drilled hole.

The experimental area contained a diluvial deposit, composed of sandy soil containing gravel with N values of five to 30 at the entry side and loam with N values of two to eight at the exit side.

The experimental procedure is shown in **Fig. 9**.

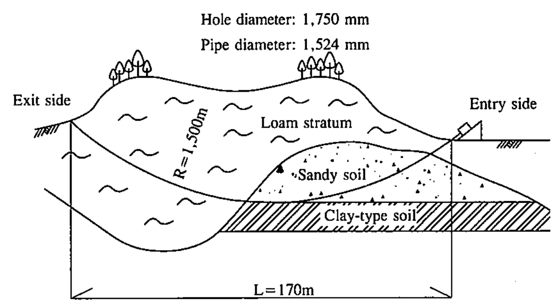

Fig. 8 Cross-sectional view of tunnel drilled in field experiment

Month	6	7	8	9	10
Leveling, temporary construction, and machine installation	○—	—○			
1) Drilling pilot hole		○–○			
2) Reaming pilot hole and replacing drill pipe			○○		
3) Pulling back main pipe		○	Preparation	○–○	
Disassembly, removal, and restoration to original condition				○—	—○

Fig. 9 Experimental procedure

Operating side	Operating procedure
Entry side	Pretension drill pipe with drilling rig
Exit side	Supply mud to face
Exit side	Start water jets
Exit side	Start cutter
Entry side	Pull back dedicated cutting head
Exit side	Stop cutter
Exit side	Stop water jets
Exit side	Discharge mud
Entry and exit sides	Pull back main pipe

Fig. 10 Operating procedure of J-PLAD method

3.2 Experiment results

The experimental results from the final stage of pulling back the 1,524-mm main pipe are presented below.

3.2.1 Establishment of efficient control method

The main pipe pulling-back stage of the conventional PLAD method basically consisted of pulling back the main pipe with the drilling rig at the entry side and had little effect on the overall progress of the microtunneling project. In the new J-PLAD method, the operation of the cutter, slide jacks and mud recirculation system at the exit side increased the pullback of the dedicated drilling head at the entry side, as shown in **Fig. 10**. Accordingly, a more efficient operating method is required.

The J-PLAD system was manually operated while each operation was checked according to the procedure formulated in the planning stage. As a result, the operating procedure shown in **Fig. 10** was clarified. In addition, the reference values observed to change from one operating stage to next, such as the tension force applied to the drill pipe from the drilling rig at the entry side before rotating the cutter, mud flow rate, cutting face mud pressure and mud feed pressure, were successfully measured and set. This made it possible to efficiently operate the J-PLAD system while stably drilling the pilot hole and pulling back the main pipe.

3.2.2 Demonstration of arch tunnel construction

It was confirmed that the dedicated drilling head built for the field experiment satisfactorily functioned and smoothly drilled the arch tunnel along the preceding drill pipe on the upward slope of the tunnel. The dedicated drilling head emerging at the exit side is shown in **Photo 3**.

3.2.3 Complete removal of drillings and stable recirculation of mud

The mud was found to be fully capable of removing clay, sand, and pieces of gravel about 50 mm in size. In the J-PLAD method, the mud is pumped into the chamber and to the front of the cutter for discharge as water jets. The fluid transport method of the J-PLAD method differs from that of the conventional mud shield method in the flow of the mud near the cutter. It was verified, however, that the mud feed and discharge flow rates varied little and that the mud could be stably recirculated despite the 2:1 difference in volume between the chamber feed mud and water jet mud.

3.2.4 Reduction in drilling force by water jet

One characteristic of the dedicated drilling head is that mud jet nozzles are installed on the front surface of the cutter. The mud jet nozzles are designed to reduce the drilling force by discharging jets of water during the drilling stage. In the sandy soil encountered in the field experiment, the drilling torque was reduced by about 30% using a water jet at the drilling speed of 25 cm/min, a jet flow rate of 1.0 m^3/min, and a jet pressure of about 20 kgf/cm^2, as compared with drilling without the benefit of a water jet. This result suggests the ability of the water jet not only reduces cutter bit wear but also increases the drilling speed.

The water jet is shown in **Photo 4**.

3.3 Future issues

In the field experiment, the J-PLAD method was used to bore only a 170-m tunnel due to the limited site area. The field experiment succeeded in obtaining drilling data and mud recirculation data as required to apply the J-PLAD method to larger and longer tunnels. It also demonstrated the capability of the J-PLAD method for drilling large arch tunnels. The authors will study the following issues to augment J-PLAD method capacity:

Photo 3 Arrival of dedicated cutting head at exit side

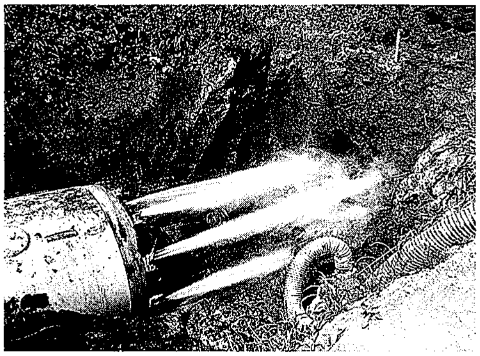

Photo 4 Water being discharged from nozzles

(1) Increase in length of tunnels drilled
(2) Increase in adaptability to difficult soil conditions, such as alternate strata of rock and gravel
(3) Decrease in size of drilling equipment and mud recirculation equipment

4. Conclusions

The field experiment conducted in Kisarazu, Chiba Prefecture, verified the performance of the entire drilling and pulling-back system and confirmed the prospect of commercializing the J-PLAD method for boring large-diameter arch tunnels.

Demand for the J-PLAD method is expected to mount more than ever as Japan heads toward the 21st century and social infrastructure improvements continue. The J-PLAD method will find increasing usage in gas, electric power, petroleum, city water and sewerage, agricultural and industrial water, and many other applications by capitalizing on the following features:

(1) It can bore tunnels up to 2,000 mm in size.
(2) It can drill at a speed several times higher than that of the conventional shield method, and since no shafts are required, construction can be completed faster.
(3) Operating tasks are performed on the ground surface, assuring maximum safety.

References

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