DEVELOPMENT OF SMALL-BORE, LONG-DISTANCE, CURVED-CONDUIT TUNNELING ROBOT

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ABSTRACT

This paper describes the application of pipe-tunneling robots for constructing small-bore (1 - 2m) tunnel conduits for underground power cables. The system makes possible long-distance, curved-conduit tunneling. The development consists of the following basic technology; (1) an automatic position-measuring system via gyro car; (2) a self-propelled, semi-shielded machine for long-distance, curved-conduit tunneling; (3) high-strength Hume pipe with resin-reinforced terminals; (4) remote control operating system. The method has been under development since 1983. Its practicality was proved in actual site tests in 1987 with routes of 100m and curvature radii of 80m.

1. Introduction

With the increase of both traffic volume and structural obstacles, new methods to freely construct underground installations without the need for surface interruptions have become increasingly important.

To meet these requirements, Tokyo Electric Power Company and Kandenko started to develop a small-bore power-cable conduit tunneling robot. The system is designed to handle conduit installations under varying conditions with diameters 1 - 2m, in segments as long as 300m.

2. Outline of Robot Method

Comparisons of basic performance between conventional methods and the long-distance, curved-conduit tunneling robot are presented below (see Table 1 and Figure 1).

Table 1. Comparative Outline of Long-Distance, Curved-Conduit Tunneling Robot

	Long-Distance, Curved-Conduit Tunneling Robot	Conventional Mechanical Pipe Jacking Method
Maximum Distance	300m	150 - 200m
Minimum Curvature Radius	80m (Both vertical and horizontal curves possible)	150m (Typically straight-line only)
Error Reference	Within 10cm/100m	10 - 20cm/100m
Daily Advance	5m/day	3m/day

The procedure under discussion specifically allows for maximum flexibility in curved tunneling. The bore is excavated by the remote-controlled, self-propelled, semi-shielded machine. Propulsion pipe (Hume pipe) is push-injected for the length of the excavated bore by primary or intermediate pushing jacks. At that time, the propulsion pipe advances along the curve with inside joint connections contacting the following pipe and outside connections open. Positioning and alignment of the push-injected piping is automatically measured by automatic position-measuring system. These data are relayed to the surface to permit required repositioning and realignment adjustments as each segment of piping is injected. Excavated soil is slurried in a bentonite mixture and conveyed to the surface for disposal by soil pump.

For straight-line tunneling, the semi-shielded machine and propulsion piping are propelled in the same manner as conventional methods, using a primary pushing jack at the starting shaft. Built-in remote-control mechanisms permit full surface control to bore tunnels on a completely unmanned basis.

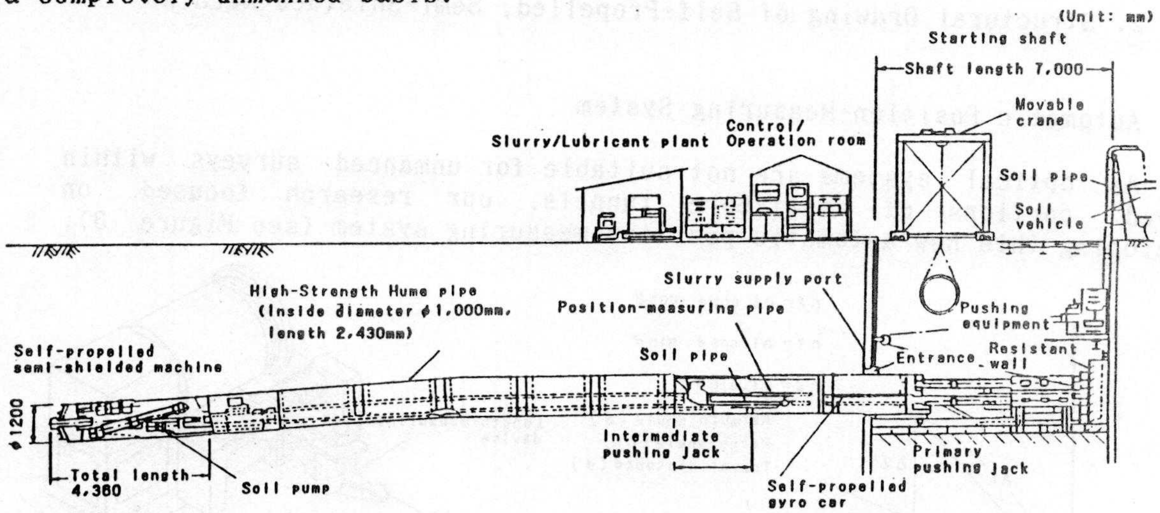

Fig. 1. Schematic Diagram of Long-Distance, Curved-Conduit Tunneling Method

3. Components

Components of this newly developed system include the following:

3.1 Self-Propelled, Semi-Shielded Machine

Considering the various types of soil encountered, a semi-shielded machine capable of handling both sandy- and clay-type soils was adopted. The device employs a spoke-type, three-blade cutting head (Figure 2 and Photo 1).

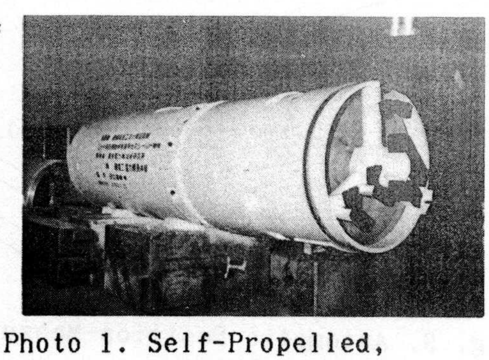

Photo 1. Self-Propelled, Semi-Shielded Machine

This semi-shielded machine uses four shield jacks for propulsion.

Each jack's stroke length is 300mm and maximum thrust is 30tf. The stroke differential is 19mm in curvature radii of 80m. When the leading head of the machine advances using the following pipe as the resistant body, a curved propulsion with a minimum radius of 80m can be achieved. A bentonite mixture is used for slurrying excavated soil, which is then carried to the surface by the screw conveyor and pressure pump through a 150mm-diameter soil pipe.

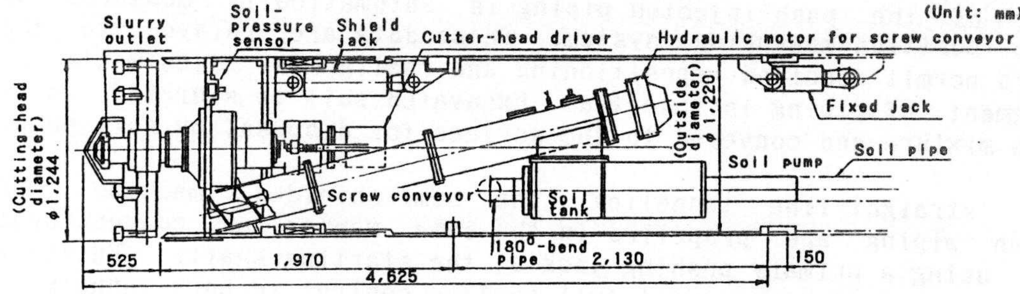

Fig. 2. Structural Drawing of Self-Propelled, Semi-Shielded Machine

3.2 Automatic Position-Measuring System

As optical systems are not suitable for unmanned surveys within curved portions of small-bore tunnels, our research focused on developing this new automatic position-measuring system (see Figure 3).

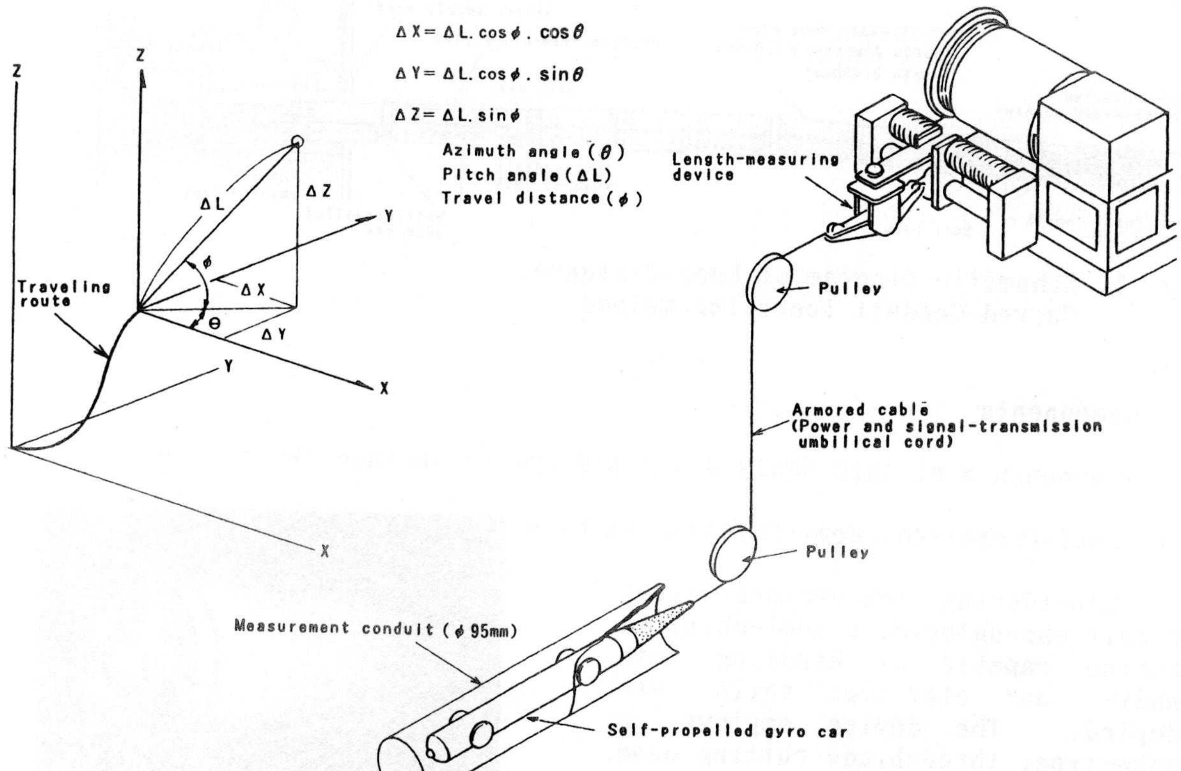

Fig. 3. Automatic Position-Measuring System

The core unit consists of a self-propelled gyro car, an armored cable and a cable-length-measuring device. The gyro car (Photo 2), which has an overall length of 1,760mm and an outside diameter of 75mm, includes a rate-integration gyro and a servo-accelerometer. The armored cable (Ø 7.6mm) hauled by the gyro car contains power and transmission lines. Measurement is carried out by running the gyro car at a fixed speed of 30m/min within a measurement conduit with an inside diameter of 95mm. Travel distance (L), azimuth (Θ) and pitch angles (Ø) are respectively measured continuously (20 times/sec) via the length-measuring device, the gyro and the servo-accelerometer, thus permitting automatic calculating of semi-shielded machine positioning and the installed conduit line.

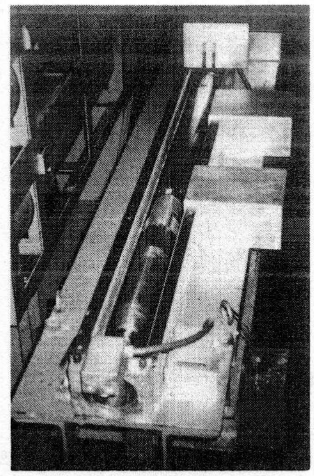

Photo 2.Self-Propelled Gyro Car

3.3 High-Strength Hume Pipe with Resin-Reinforced Terminals

As the curve pressure is concentrated on inside angles in curved installations, Hume pipe terminals must be specially reinforced. High-strength Hume pipe with resin-reinforced terminals is used for this purpose (outside diameter 1,200mm; section length is 2,430mm). This pipe meets usual compression standards of 700kgf/cm^2 at the center; rims are specially reinforced at both ends by 30cm-polyester-resin bands to withstand a compression force of 1,500kgf/cm^2 (see Figure 4 and Photo 3). Rubberized packing is used to prevent water infiltration even at curved joints.

The primary pushing equipment for the Hume pipe conduit consists of four 150tf jacks in the primary shaft and auxiliary pushing equipment of eight 25tf jacks in the intermediate jacking pipe.

3.4 Remote-Control System

A remote-control system operates the semi-shielded machine and controls the automatic position-measuring system. Operational data of the device, such as soil pressure, revolutions of the screw conveyer, jack stroke and pump pressure, are monitored on a real-time basis and conveyed to the surface. Based on this data, the operator can adjust the equipment via remote-control for such things as shield/soil pressure, positioning, direction and soil discharge.

In controlling the automatic position-measuring system, the self-propelled gyro car is remote-controlled and such data as distance, azimuth and pitch angles are sent to the operating room where the formed line and the position of the semi-shielded machine are automatically calculated.

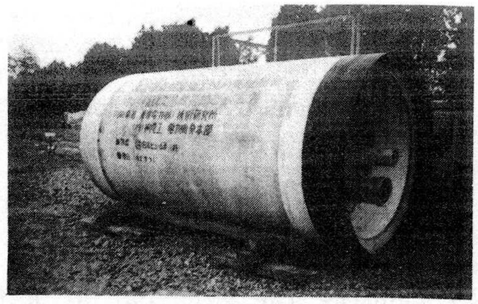

Photo 3. High-Strength Hume Pipe with Resin-Reinforced Terminals

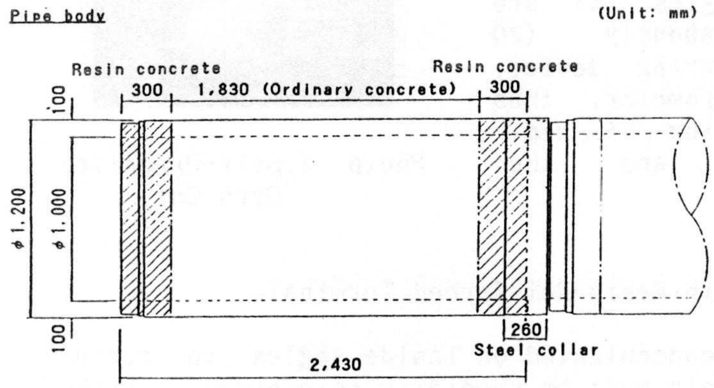

Fig. 4. Schematic Diagram of High-Strength Hume Pipe with Resin-Reinforced Terminals

4. Site-Demonstration Tests

In 1987, we conducted site-demonstration tests in Japan's Ibaragi Prefecture.

4.1 Test Outline

In these demonstration tests, various measurements were made on the following items to confirm overall performance of the long-distance, curved-conduit tunneling method.

(1) Directional control and self-propelling performance of the semi-shielded machine.
(2) Measuring performance of the automatic position measuring system.
(3) Load-pressure performance of the high-strength Hume pipe with resin-reinforced terminals.

4.2 Testing Route and Test Ground

Figure 5 shows the outline of the demonstration test route. The route length was 102m. This included four curved portions; two with radii of 80m horizontally, and two with 80m-radii in the longitudinal plane. Tunnel depth was 2 - 3m.

The test site consisted of loam and sandy-clay soil with an N value of 2 - 4 (see Figure 6). The main test results are as follows.

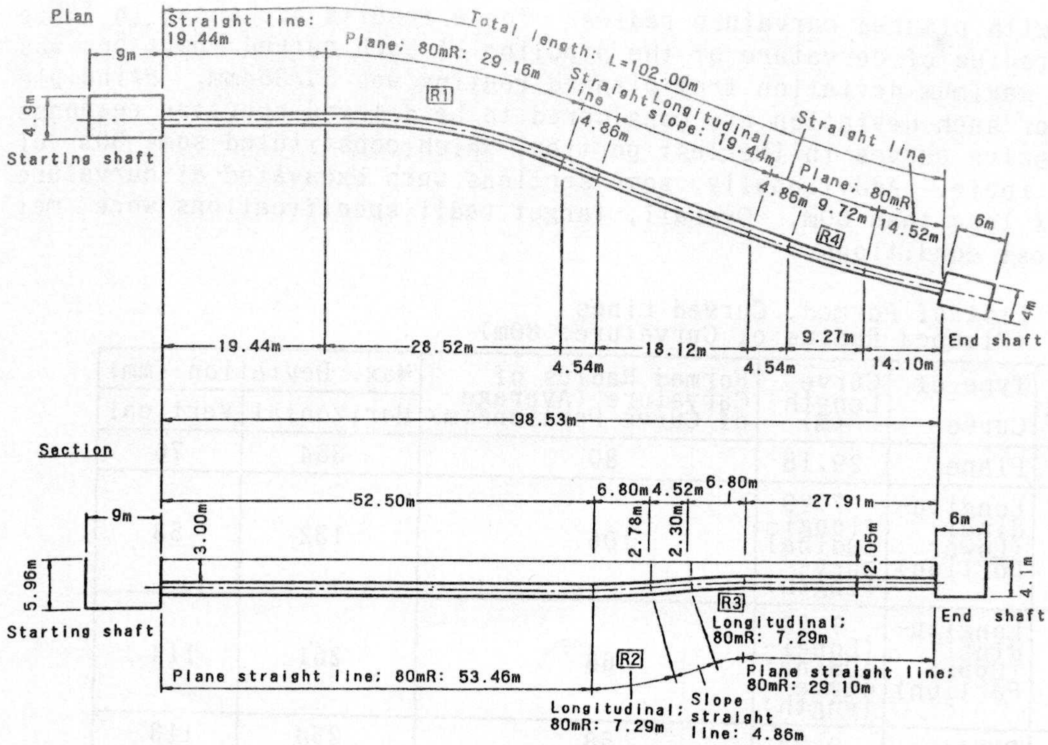

Fig. 5. Planned Route for Demonstration Test

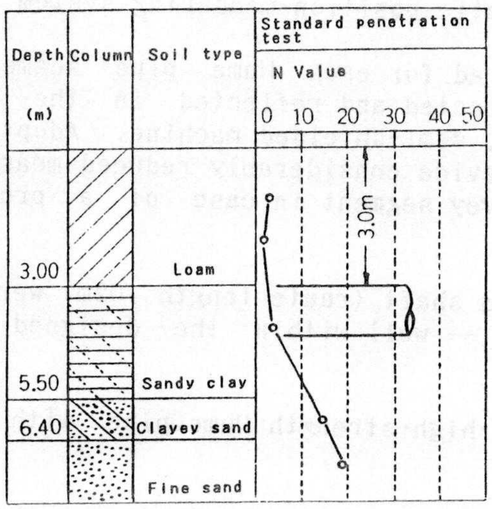

Fig. 6. Geological Column (Starting Shaft Area)

4.3 Test Results

(1) Directional control and self-propelling performance of self-propelled, semi-shielded machine.

The self-propelling performance of the semi-shielded machine met design specifications, as shield jacks operated with proper strokes based on a planned value (about 30cm) during excavations.

Following excavation, the formed shape of the curved portion was surveyed and directional control performance was confirmed by comparing results with planned curvature radius. These results are shown in Table 2. The radius of curvature of the pipeline at each curved portion was 106/58m; maximum deviation from planned routing was 53/364mm. Principle causes for such deviation are considered to be delayed operator response and excessive curves in the test portion, which constituted some 50% of the test route. Additionally, some sections were excavated at curvature radii of less than 80m. Overall, target radii specifications were met in all test conditions.

Table 2. List of Formed, Curved Lines
(Planned Radius of Curvature: 80m)

Section	Type of Curve	Curve Length (m)	Formed Radius of Curvature (Average of Curve Portions:m)	Max. Deviation (mm)	
				Horizontal	Vertical
R1	Plane	29.16	80	364	76
R2	Longitudinal (Lower Portion)	7.29 (longitudinal curve length)	106	132	53
R3	Longitudinal (Upper Portion)	7.29 (Longitudinal curve length)	68	261	114
R4	Plane	9.72	58	254	113

(2) Measuring performance of automatic position-measuring system

The formed line was measured for each Hume pipe segment and deviations from planned line corrected and reflected in the control performance of the self-propelled, semi-shielded machine. Adoption of the automatic position-measuring device considerably reduced measurement time to about 10 minutes per survey segment in case of a propulsion distance of 100m.

Measurement errors at the end shaft (route length 102m) were 60mm horizontally and 15mm vertically — well within the designed target range for conduit lengths of 100m.

(3) Load-pressure performance of high-strength Hume pipe with resin-reinforced terminals

Prior to the demonstration test, each part was tested on the ground to confirm load performance of the high-strength Hume pipe. These tests were conducted under a maximum thrust of 200tf by jack application at a curvature radius of 80m.

During these demonstration tests, propulsion load and strain distribution on the Hume pipe terminals were measured under conditions that would be encountered in typical underground installations. Results are presented in Figure 7.

These tests indicated a maximum pressure distribution at touch-point terminals of some 200 μ (a compressive stress of 62kgf/cm^2) at a thrusting pressure of 40tf. In the test on the ground, the compressive stress at a load of 200tf was 310kgf/cm^2, which indicates sufficient strength. Piping was visually inspected following these tests to confirm.

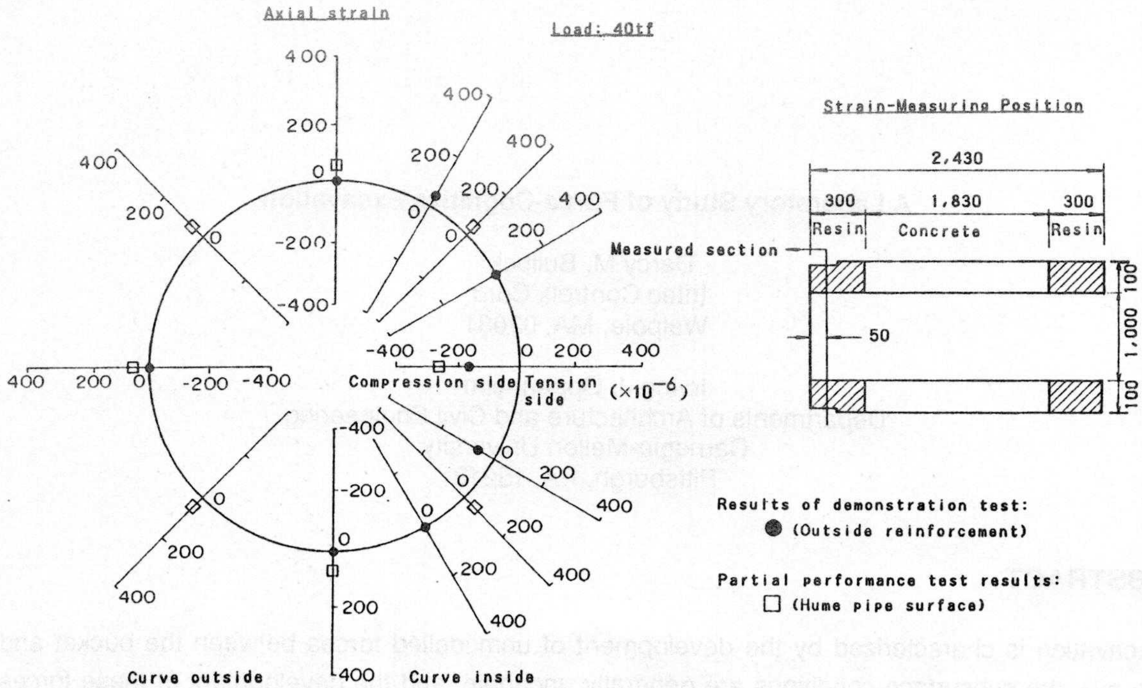

Fig. 7. Strain Distribution of High-Strength Hume Pipe
(Resin Section) during Propulsion at Curved Portion

5. Conclusion

The following relevant technologies were carried out in the development of small-bore, long-distance, curved-conduit tunneling via robot for underground power cables.

1) A self-propelled, semi-shielded machine.
2) Automatic position-measuring system.
3) High-strength Hume pipe with resin-reinforced terminals for curved tunneling installations.
4) Remote control operating system.

As a result of these site-demonstration tests using this construction method, the following knowledge was obtained.

1) The self-propelled, semi-shielded machine can sufficiently cope with curved excavations with radii of 80m.
2) The automatic position-measuring system has an accuracy of 10cm indistances as long as 100m.
3) The Hume pipe is sufficiently strong to withstand stress concentrations at pipe terminals during curved excavations.

In addition, we measured the soil pressure at the sides of the pipe and behavior of the peripheral soil but found no abnormality. We plan to use this robot for 226m power conduit tunneling which includes two curved portions in Tokyo.