Pipe Jacking Method for Long Curve Construction

By Yoshihiko Nomura,[1] Hiroshi Hoshina,[2] Hiroshi Shiomi,[3] and Takao Umezu[4]

Abstract: The D301 pipe jacking method is the first to accomplish long spans, curves and high speed construction in the field of small diameter (300 mm) tunneling. The design of the system components are described: tunneling machine with directional control ability, jacking machine, power unit, and control unit which contains a microprocessor. As a result of field tests in about 100 m in length with a 200 curvature radius, the following capabilities are confirmed: the span length is up to 100 m, the curvature radius is down to 200 m, it is useable in either cohesive or sandy soils having *N*-curves up to 10, and the construction speed is up to 3 m/h.

Introduction

In Japan, almost all conduits for telecommunication cables are laid under public roads. The conduits are generally constructed by a cut and cover construction method. However, this method has become more and more difficult to employ, especially in big cities, due to traffic obstruction, underground facilities congestion, and adverse effects on the environment. Therefore, a tunnel construction method which has less effect on the environment, is required in place of the conventional cut and cover method.

At present, a small diameter (300 mm) tunneling method is used in the construction of underground power, gas, and water facilities. At NTT, a horizontal augering method, a pipe jacking method, and other methods are used, both under railway track beds and beneath public roads. However, the present tunnel length limit is only 30–50 m, since conventional methods do not have good directional correction characteristics. Therefore, the development of a new method with directional correction ability is desirable.

The D301 pipe jacking method (D301 method) responds to these needs by featuring a directional control system which combines a directional correction mechanism and a positional attitude measurement function.

To economize in tunnel construction and to reduce the adverse effects on traffic and the environment, speeding up construction work is desirable. Taking into consideration that ground with an overburden thick-

[1]Engr., Ibaraki Electrical Communication Lab., Nippon Telegraph and Telephone Public Corp., Tokai, Ibaraki-ken, 319-11, Japan.
[2]Staff Engr., Ibaraki Electrical Communication Lab., Nippon Telegraph and Telephone Public Corp., Tokai, Ibaraki-ken, 319-11, Japan.
[3]Engr., Ibaraki Electrical Communication Lab., Nippon Telegraph and Telephone Public Corp., Tokai, Ibaraki-ken, 319-11, Japan.
[4]Engr., Ibaraki Electrical Communication Lab., Nippon Telegraph and Telephone Public Corp., Tokai, Ibaraki-ken, 319-11, Japan.

Note.—Discussion open until November 1, 1985. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on August 28, 1984. This paper is part of the *Journal of Construction Engineering and Management*, Vol. 111, No. 2, June, 1985. ©ASCE, ISSN 0733-9364/85/0002-0138/$01.00. Paper No. 19766.

ness less than several meters has relatively high compressibility and that tunnel diameters will be small, the D301 method utilized nonmuck-discharge as its boring method. By the realization of a directional control system plus nonmuck-discharge boring, the D301 method enables rapid construction that includes long spans and curves.

The D301 system design and field test results of tunnel construction is described.

Design of D301 Pipe Jacking System

System Composition.—The development philosophy of the D301 method is shown in Fig. 1. A list of the important components in Fig. 1 is as follows:

1. Head incline-drive directional correction mechanism.
2. Position and attitude sensors for both magnetic measurement and bending angle measurement.
3. Nonmuck-discharge penetrating device.

Various considerations of these components resulted in the design of the D301 system shown in Fig. 2. As shown in Fig. 2, the D301 system has four main components: a tunneling machine, a jacking machine, a power unit, and a control unit. Fig. 3 shows the tunneling machine in use. The main specifications for this system are shown in Table 1.

Tunneling Machine.—The tunneling machine (1) has three main sections: a head, which is driven into the ground; a fore part, which inclines and drives the head; and a hind part, which bends on curved sections. The special features of this machine are nonmuck-discharge penetration, a directional correction function, and positional attitude measurements.

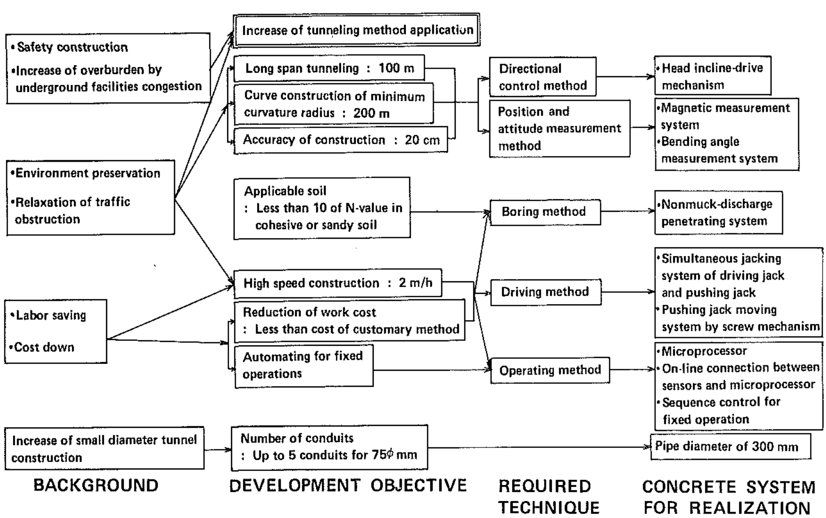

FIG. 1.—Philosophy of Development

J. Constr. Eng. Manage., 1985, 111(2): 138-148

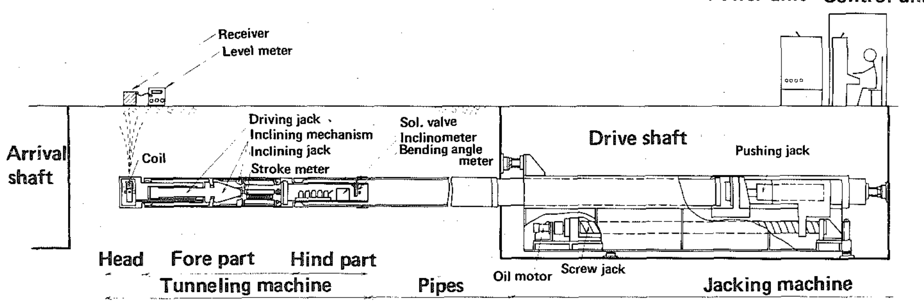

FIG. 2.—Pipe Jacking Method (D301)

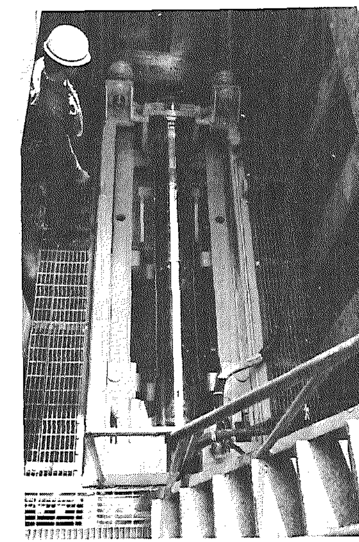

FIG. 3.—Tunneling Machine in Use

TABLE 1.—Specifications

Section (1)	Item (2)	Specification (3)
Tunneling machine	Inclining angle	$-1.5°–0°–+1.5°$
	Driving jack thrust	1 MN
	Outside diameter × length	ϕ350 mm (max) × 3,080 mm
Jacking machine	Available stroke	2,650 mm
	Pushing jack thrust	2 MN
Power unit	Power	14 kW (max)
	Hydraulic pump flow rate	1.6 L/min, 10.6 L/min, 35 L/min
	Oil pressure	70 MPa (max)
	Length × width × height	900 mm × 1,600 mm × 1,200 mm
Control unit	Switch	Jack operation, automation for fixed operations, et al.
	Display	Inclinometer, bending angle meter potentiometer, et al.
	Microprocesser	Built in type, on-line connection with sensors
	Length × width × height	545 mm × 600 mm × 1,000 mm

Information gained from the positional attitude sensors is used by the system controller to maintain directional accuracy during drilling by utilizing the incline-drive mechanism.

Nonmuck-Discharge Penetration.—Since the D301 method utilizes the nonmuck-discharge method, the more the driving jack, by which the head is driven into ground, thrusts, the further the head will penetrate. Therefore, the largest jack, 1 MN in thrust, which is able to be mounted in the fore part of the tunneling machine is utilized as the driving jack.

Directional Correction Method.—The driving jack is held so that it can incline freely due to the ball joint attached to the front end of the body. When the inclining mechanism located on the rear end of the driving jack is utilized by the inclining jack, the driving jack inclines. Then, the head which is firmly attached to the driving jack inclines in the necessary direction. By adjusting the four inclining jacks' strokes, the head movement can be set in any direction at a maximum angle of 1.5°. Then, the head is driven into the ground in the appropriate direction. The body and the pipes are then jacked forward following the head. In this way, necessary directional correction is maintained.

Position and Attitude Measurement.—To perform appropriate directional correction, it is necessary to measure the position and attitude of the tunneling machine in reference to the planned line. Up to now, optical measurement and laser light measurement have been used for this purpose, but such measurement is limited to use in short distance, straight line applications, where it is possible to see from end to end. Since the D301 method is intended for use in longer distances and in curved line applications, conventional measurement methods cannot be used. Measurement methods peculiar to the D301 method are the horizontal position and the yawing angle measurement methods.

The horizontal position measurement is accomplished by magnetic sensing (2,6). The fundamental constitution of the measurement is shown

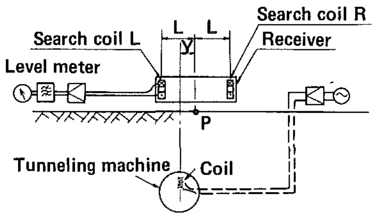

FIG. 4.—Fundamental Constitution of Magnetic Measurement

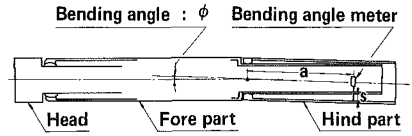

FIG. 5.—Principle of Bending Angle Measurement

in Fig. 4. In this measurement, the magnetic field emitted from a coil mounted inside the head is detected by a search coil set on the ground surface. If V_L is taken as the induced voltage in search coil L, V_R is taken as one in search coil R, and $2L$ is the distance between the two search coils, then the horizontal position Y from a reference point P is given by

$$Y = \frac{L(V_R - V_L)}{(V_R + V_L)} \quad \text{(1)}$$

To reduce the number of measurements on the road surface during this survey, an angle measurement device is provided which can estimate the yawing angle from the bending angle between the fore part and the hind part of the tunneling machine (3). Fig. 5 shows the principle of the bending angle measurement. The hind part is composed of an outer pipe and an inner pipe which is fixed to the fore part. The distance S between the outer pipe and the inner pipe can be measured by a linear motion potentiometer, the bending angle meter. If S_0 = the distance when bending angle $\phi = 0°$ and a = the distance between the top end of the hind part and the bending angle meter, then the bending angle ϕ is given by

$$\phi = \tan^{-1}\left(\frac{S - S_0}{a}\right) \quad \text{(2)}$$

By the use of the bending angle measurement, the magnetic measurement need be done once every 2.5 m of tunneled length, resulting in minimal traffic obstruction on the road under which the tunnel is being driven.

These measurement method equipments are compact and inexpensive, so they are very well suited for use with the small diameter tunneling method as well as the D301 method.

Jacking Machine.—The jacking machine is composed of the pushing jack which jacks the pipes forward, a screw jack which moves the pushing jack, and a base which houses these components. The distinctive feature of this equipment is that, by sequentially moving and setting the pushing jack which has a short stroke of 41.67 cm, continuous jacking throughout the whole length of the pipe (250 cm) can be achieved in six strokes (6 × 41.67 = 250 cm).

TABLE 2.—Combinations of Flow Rate

Process (1)	Operation of actuator (2)	Flow rate (3)	Note (4)
Setting head driving direction	Extending inclining jack	1.6 L/min	
Driving head	Extending pushing jack	10.6 L/min	
Jacking body and pipes	Extending driving jack	10.6 L/min	Simultaneous jacking
	Contracting driving jack	1.6 L/min	
Moving pushing jack forward	Contracting pushing jack	10 L/min	Simultaneous jacking
	Rotating oil motor counterclockwise	16 L/min	
Moving pushing jack backward	Contracting pushing jack	10 L/min	Simultaneous jacking
	Rotating oil motor clockwise	10–25 L/min	

As a result of an experiment in a loam floor, the ratio of jacking thrust to tunneled length was almost constant at about 10 kN/m. Therefore, the pushing jack thrust is estimated to be 1 MN over a span length of 100 m. 1 MN multiplied by a safety factor of 2 makes 2 MN of thrust to the pushing jack.

Power Unit.—The power unit operates the various actuators, and is composed of hydraulic pumps which generate high oil pressure, an oil tank, motors to drive the pumps, magnetic valves, pressure gages, and other accessories. Its special feature is a mechanism that can select combinations of the hydraulic pumps and supply a small or large flow rate of oil as shown in Table 2. Utilizing this function, simultaneous jackings are possible.

Control Unit.—The control unit is composed of switches which operate each of the system's devices, a data output unit which displays measurement values from each of the sensors, a microprocessor and connectors to link the power cable, control cable, and measurement cables.

There is an on-line connection between the attitude sensors and the microprocesser built into the control unit. With the microprocesser, comparative calculations can be performed in reference to the planned line, and the appropriate directional correction operations can be carried out.

In addition, the control unit provides the advantage of possible automation for fixed operations from driving the head to moving the pushing jack in the tunneling process.

Tunneling Method.—Fig. 6 shows the tunneling process using the D301 system.

The driving jack is extended by recoil from the jacking machine, and the head is driven into the ground. The effectiveness of this method is further enhanced, since soil does not have to be discharged. After the completion of one stroke (approximately 42 cm), the driving jack contracts, and the pushing jack, which is synchronized with it, extends and the pipes are pushed forward. This is called the simultaneous jacking method. After completing the stroke, the pushing jack and the screw jack contract and push forward, respectively, at the same time, providing the initial position ready for a new stroke. This completes a one

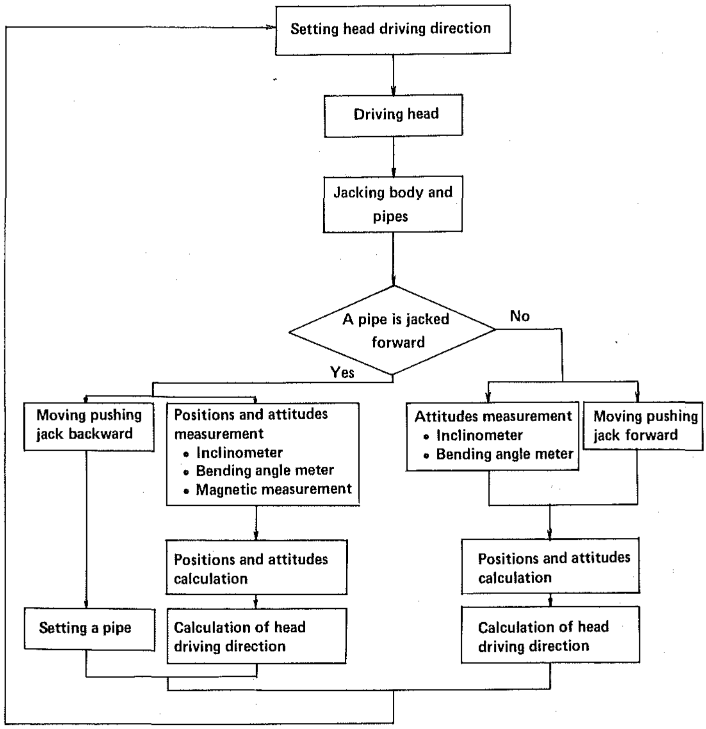

FIG. 6.—Tunneling Processes

stroke cycle. As previously explained, a pipe 250 cm in length is jacked forward with six repetitions of the stroke cycle. Once the pipe is jacked forward, the pushing jack is returned to its initial rear-end position by the screw jack. Next, a new pipe is set in place in the open space and the cycle is ready to be repeated. In this way, new pipe sections are laid. It is now possible to continue accurately up to about 100 m.

Field Test Results

Using the D301 system, tunnel construction field tests of 330 m in total length have been carried out as shown in Table 3.

TABLE 3.—Record of Tunnel Construction Field Test

Test (1)	Span length (m) (2)	Curvature (m) (3)	Overburden thickness (m) (4)	*N*-value (5)	Cone penetration resistance (MPa) (6)
A	90	200	2.4	—	1.0–2.0
B	90	200	2.4	—	0.7–4.1
C	50	150	2.0	2–5	1–1.3
	50	100	2.7	2–5	1–1.3
	50	Straight	1.5	2–5	1–1.3

J. Constr. Eng. Manage., 1985, 111(2): 138-148

TABLE 4.—Tunnel Construction Field Soil Characteristics

Test (1)	Soils (2)	Gravel (%) (3)	Sand (%) (4)	Silt (%) (5)	Clay (%) (6)	Moisture ratio (%) (7)	Void ratio (8)
A	Clay	0	6	24	70	55	1.5
B	Sand	1	80	9	10	25	0.81
C	Loam	0	35	64	1	95	2.6

As a result of these tests, the following capabilities of the D301 system were confirmed.

Applicable Soil.—In the D301 method, driving jack thrust is an important factor in deciding on applicable soil. Though applicable soil was frequently shown by *N*-value, standard penetration test haven't been performed to all soil of the field tests as shown in Table 4. Therefore, applicable soil was discussed as follows. Originally, the relations between *N*-value and cone penetration resistance qu, in which qu(Mpa) = 0.2 N in a cohesive soil and qu(MPa) = 0.4 N in a sandy soil, were proposed by Schmertmann (5). Using these relations and qu in Table 3, the *N*-value in Test A is 5–10, and in Test B is 2–10. Also, the *N*-value of 2–5 in Tect C was measured by standard penetration test. Next, in Tests A, B and C, their respective driving jack thrusts were 70–110 kN, 50–300 kN and 60–140 kN. Therefore, even though available driving jack thrust is up to 850 kN because of oil pressure loss, the tunneling machine can be successfully used in soil of objective *N*-value up to 10.

On the other hand, the deformation characteristics in soil due to driving of the head are an important problem. Therefore, the author has been studying it by means of a model test (4).

Here, NTT has surveyed soil distribution with an overburden thickness of several meters, to which the tunneling method has been applied, in the cities of Tokyo, Osaka, and Nagoya. By the results shown in Fig. 7, it is assumed that the D301 method can be applied to 46% of the area in these large cities where the *N*-values are less than 10.

Span Length.—The pushing jack thrust is the limiting factor in the span length. Test results for the pushing jack thrust are shown in Fig.

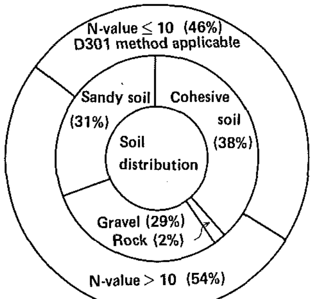

FIG. 7.—Soil Distribution in Big Cities in Japan

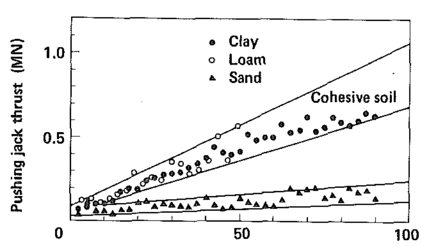

FIG. 8.—Pushing Jack Thrust

J. Constr. Eng. Manage., 1985, 111(2): 138-148

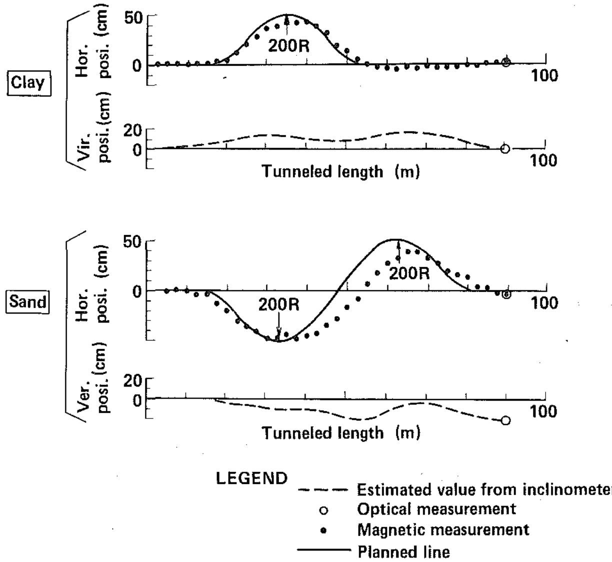

FIG. 9.—Plan and Profile Showing Tunneling Route

8. From the figure, the pushing jack characteristics were clarified as follows:

1. The pushing jack thrust increases in proportion to the tunneled length.
2. Both in the clay and in the loam, the thrust in a span length of 100 m became about 1 MN.
3. In sand, the thrust was very small. From this, it is assumed that the soil tunnel made by the driving head was self-supported in the loose sand used in this field test.

As a result, it was confirmed that a jacking machine having 1.95 MN in available thrust is adequate for a span length of 100 m.

Tunnel Curvature.—Plans and profiles showing tunneling routes of Test A and Test B are shown in Fig. 9. The integrals from 0 m–90 m of the sines of the pitch angles measured by the inclinometer over the tunneled length were corrected by values measured optically. Thus, the broken lines estimated from the pitch angles were obtained. The black circles are the values from magnetic measurement. As shown in Fig. 9, the tunneling machine was controlled along a planned line involving curves 200 m in radius, and with an accuracy of 20 cm. Also, in Test C in a loam floor, tunnels of the same quality were constructed. As a result of these tests, it was clarified that the D301 method was applicable to the curve construction with an objective curvature radius of 200 m.

Furthermore, information with the directional correction ability obtained by these tests was listed as follows:

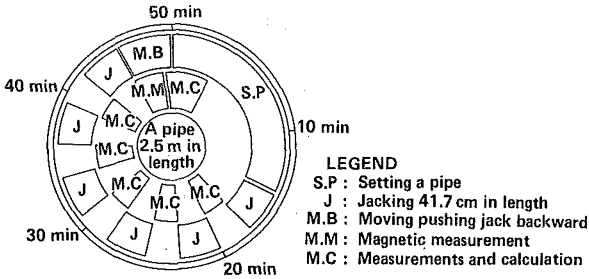

FIG. 10.—Cycle Time

In the horizontal direction

1. The directional correction ability increases in proportion to the head inclining angle in the region of $-1.5°–+1.5°$.
2. In a loam floor, a clay floor and a sand floor, the directional correction abilities were, respectively, 70 m, 134 m and 186 m in curvature radius at a maximum head inclining angle of 1.5°.

In the vertical direction

3. The directional correction ability tends to incline up or down, i.e., with a small overburden, an upward inclination was seen. In the boundary between different compressible soil layers, an inclination towards a high compressible soil was seen, and in very loose sand, a downward inclination was seen. Therefore, to hold a constant attitude, an appropriate head inclining angle, to cancel the inherent inclination, should be superimposed.

Here, since clay doesn't have water permeability, it has low compressibility; since sand has little void, it has low compressibility too. Therefore, it is assumed that deformed clay or sand around the body presses the body, and the directional change of the body is decreased. As a result, the directional correction ability in clay or sand was smaller than one in loam.

Construction Speed.—In the D301 method, the processes, namely, the moving pushing the jack backward, the magnetic measurement and setting pipe were conducted every 2.5 m of tunnel, therefore, representing one cycle. Test results concerned with cycle time are shown in Fig. 10. In cooperation with the nonmuck-discharge method, automation for fixed operations and introduction of a microprocesser, the rapid construction of 3 m/h (2.5 m per 50 min), which exceeds the objective speed of 2 m/hr, has been accomplished.

Conclusion

By the use of a directional control system, which combines a directional correction function and position and attitude measurement function, the D301 method makes possible laying conduits in 100 m lengths as well as work in which the radius of curvature is 200 m.

J. Constr. Eng. Manage., 1985, 111(2): 138-148

Since this method does not involve muck discharge, work speed is fast, the work itself is easy and the size of the shaft is small. Also, the method can be used by inexperienced workers, since a microprocesser computes and displays the work direction and position, as well as any deviation from the planned line, and indicates the appropriate corrective operation to perform.

Because of the development of the D301 method, the day is coming when it will be possible to start conduit construction at sites where it was once thought impossible.

Acknowledgment

The authors wish to express their deep appreciation to Mr. Nobuya Kojma, Dr. Naoya Uchida, Mr. Yasutoshi Yamagishi, and Mr. Takenori Morimitsu for their invaluable comments and suggestions during the course of this investigation. Also, the authors gratefully acknowledge the assistance given by Mr. Kazuyuki Ichikubo.

Appendix I.—References

1. Nomura, Y., Hoshina, H., Shiomi, H., and Umezu, T., "Directional Controllable Tunneling Machine Designing and Characteristics," *Proceedings of the Japan Society of Civil Engineering*, No. 352, 1984, pp. 99–107 (in Japanese).
2. Nomura, Y., Hoshina, H., and Umezu, T., "Method to Measure Horizontal Position of Tunneling Machine," *Proceedings of the Japan Society of Civil Engineering*, No. 358, 1985 (in Japanese).
3. Nomura, Y., "A Method to Measure Yawing Angle and Horizontal Position of Tunneling Machine," *Transactions of Institute of Electronics and Communication Engineers of Japan*, Vol. J67-B, No. 6, 1984, pp. 615–621 (in Japanese).
4. Nomura, Y., "Study on End Resistance of Horizontal Penetration in Sandy Floor," *Transactions of the Japan Society of Civil Engineering*, Vol. 15, 1985, pp. 350–354.
5. Schmertmann, J. H., "Static Cone to Compute Static Settlement over Sand," *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 96, No. SM3, May, 1970, pp. 1011–1043.
6. Umezu, T., Nomura, Y., and Hoshina, H., "A Method to Measure Horizontal Position of Tunneling Machine," *Transactions of Institute of Electronics and Communication Engineers of Japan*, Vol. J67-B, No. 6, 1984, pp. 690–691 (in Japanese).

Appendix II.—Notation

The following symbols are used in this paper:

a = distance between top end of hind part and bending angle meter;
L = (distance between two search coils)/2;
N = N-value;
qu = cone penetration resistance;
S = distance between outer pipe and inner pipe of hind part;
S_0 = distance S when bending angle ϕ equals zero degree;
V_L = induced voltage in search coil L;
V_R = induced voltage in search coil R;
Y = horizontal position of tunneling machine; and
ϕ = bending angle.