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*Steel Pipe*

# Development of Long Span Pipe Jacking Method for Laying Underground Pipe

Kohzo Akahide, Tomoya Fujimoto, Eiji Nagano, Hiroshi Sasaki, Takashi Takeuchi, Hatsuji Doi

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When it is difficult to use the conventional open-cut method for laying pipe underground, a pipe jacking methods is often utilized. In such a case, a longer span is more desirable for actual construction because of the potential cost saving, construction efficiency, minimization of traffic interruption, and other resultant advantages. This paper discusses on improved technique which was implemented by using the Komatsu Iron Mole as a basis and by adding thereto several features such as the pipe laying technique utilizing incremental jacking force, reinforced slurry discharge function, improved direction control devices, etc., in a full-scale field test for a distance of a 200-m span employing 500-mm diameter pipe. The principal results obtained were the following: (1) Long span pipe jacking method was successfully used for a distance of a 200-m straight line. (2) Three types of pipe, namely, double walled pipe, expanded pipe and bare pipe which previously sustained buckling forces were all advanced smoothly through the soil. (3) A procedure for evaluating the main pipe jacking force was confirmed, and brief equations to estimate the maximum jacking force and its probable location were proposed. (4) High precision jacking at an accuracy of ±40mm deviation in horizontal as well as vertical directions was achieved.



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# Development of Long Span Pipe Jacking Method for Laying Underground Pipe*


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***Synopsis:***

*When it is difficult to use the conventional open-cut method for laying pipe underground, a pipe jacking method is often utilized. In such a case, a longer span is more desirable for actual construction because of the potential cost saving, construction efficiency, minimization of traffic interruption, and other resultant advantages. This paper discusses an improved technique which was implemented by using the Komatsu Iron Mole as a basis and by adding thereto several features such as the pipe laying technique utilizing incremental jacking force, reinforced slurry discharge function, improved direction control devices, etc., in a full-scale field test for a distance of a 200-m span employing 500-mm diameter pipe. The principal results obtained were the following:*

*(1) Long span pipe jacking method was successfully used for a distance of a 200-m straight line.*

*(2) Three types of pipe, namely, double walled pipe, expanded pipe and bare pipe which previously sustained buckling forces were all advanced smoothly through the soil.*

*(3) A procedure for evaluating the main pipe jacking force was confirmed, and brief equations to estimate the maximum jacking force and its probable location were proposed.*

*(4) High precision jacking at an accuracy of ±40 mm deviation in horizontal as well as vertical directions was achieved.*


## 1 Introduction

In piping work in urban and suburban areas in which the open-cut method is difficult to use, the jacking method which employs small- and medium-diameter pipe with a jacking distance of less than 50 to 70 m is widely used. However, from the viewpoints of economy, safety, and complaints of nearby residents about the annoyance caused by the piping work, it has become necessary to develop a pipe jacking method which can make the above-mentioned jacking distance as long as possible to reduce the number of pits and minimize the traffic interruption.[1)]

Recently, the authors have taken up research and development of a long span pipe jacking method for laying pipe underground based on Komatsu's Iron Mole which has a span of more than 200 m, and carried out a field pipe-laying test. As a result, the findings may be put into practical utilization, and the principal results are described below.

## 2 Pipe Jacking Method

The pipe jacking method employed in this test used the Komatsu Iron Mole as a basis, to which various software and hardware techniques were added for the purpose of extending the jacking distance.

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### 2.1 Komatsu Iron Mole

#### 2.1.1 Basic units

As shown **Photo 1**, it consists of a hydraulic unit, control unit, and rear jack mount. The specification of the basic equipment is shown in **Table 1**. Applicable pipe diameters are 250 to 900 mm.

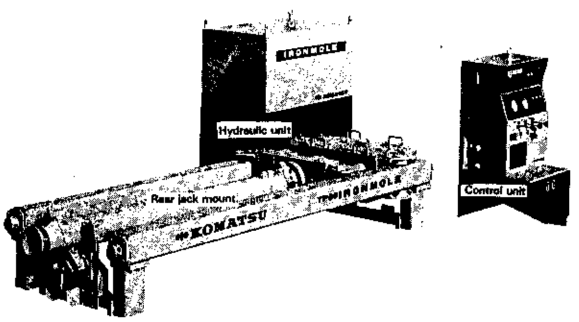



Photo 1 Basic units

Table 1 Specifications of basic units

| | |
|---|---|
| Hydraulic unit | 1 366 mm$L$ × 929 mm$W$ × 1 553 mm$H$ |
| Frequency | 50/60 Hz |
| Power required | 33 kW |
| Voltage required | 200 V (3-phase AC) |
| Weight | 970 kgf |
| Control unit | 727 mm$L$ × 689 mm$W$ × 1 564 mm$H$ |
| Power required | 150 W |
| Voltage required | 100 V (AC) |
| Weight | 250 kgf |
| Rear jack mount | 3 686 mm$L$ × 1 300 mm$W$ × 745 mm$H$ |
| Max. pushing force | 200 tf |
| Stroke | 450 mm |
| Weight | 2 230 kgf |

#### 2.1.2 Operation procedure

The operation procedure is shown in **Fig. 1**, and a two-step process is adopted in which first, a pilot pipe penetrates the ground along the proposed route, and then main pipe traces the pilot pipe.

(1) First, the starting and arrival pits are constructed, and a jacking frame is installed in the starting pit. The pilot head is then mounted.
(2) The rear jack mount inserts the pilot head into the ground.
(3) The pilot pipe is connected to other pipes to propel the pilot head.
(4) The pilot head reaches the arrival pit, completing the straight pilot hole. The pilot head is then recovered.

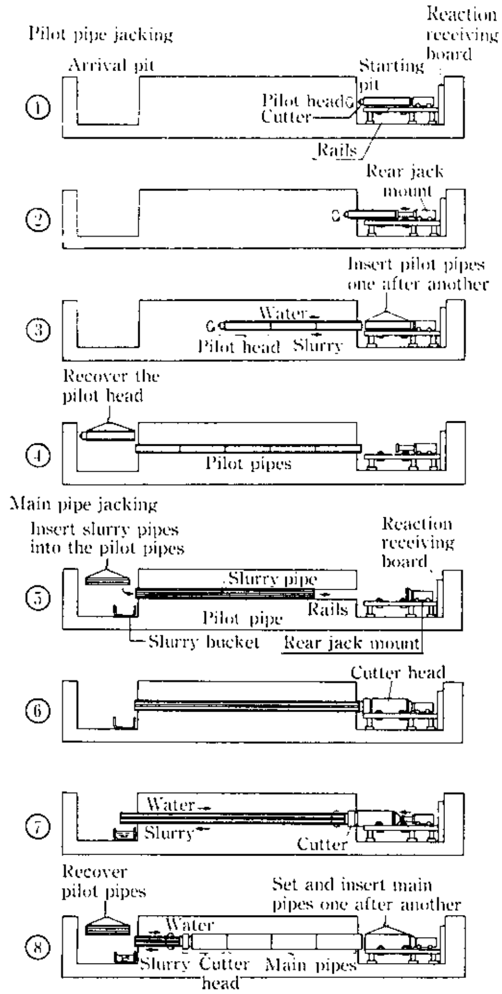



Fig. 1 Construction procedure

(5) The slurry pipe is inserted into the pilot pipe at the arrival pit end and pushed through to the starting pit.
(6) The cutter head is installed on the main pipe jacking, and connected to the water-supply/slurry-discharge unit at the starting pit.
(7) The cutter head advances, guided by the pilot pipes and pushing them forward, enlarging the pilot hole. Soil excavated by the cutter head is carried to the arrival pit in the form of slurry through the slurry-discharge pipe.
(8) As the cutter head goes forward, the main pipes are inserted one by one behind it from the rear jack mount. The pilot pipes are pushed out to the arrival pit and recovered one by one. When the cutter head emerges at the arrival pit, the pipe laying operation is completed.

#### 2.1.3 Features

Features of the Komatsu Iron Mole include the following: High precision jacking is realized; should any trouble occur, it can be judged at the jacking point whether the piping work should be continued; a wide range of soils can be dealt with by changing attachments; the pit can be made smaller if a split-type is employed; and there is a wide variety of applicable pipe diameters.

### 2.2 Coping with Long-Distance Jacking

To accomplish long-distance pipe jacking, the following technical improvements have been added to the conventional Komatsu Iron Mole:

(1) Increased Jacking Force
In the previous system, maximum jacking force was 150 t, which has been increased to 200 t.

(2) Reinforcement of Slurry Discharge Function
The longer the length of the slurry pipe becomes, the more the friction loss of fluid increases. To overcome this phenomenon, a vacuum unit is inserted into the outlet loop of the slurry pipe so that a suction force is exerted as shown in **Fig. 2**.

(3) Improved Direction Control
Two translucent amorphous silicon elements for light detection are installed in the pilot head, and both the azimuth angle and the tilt angle are calculated by introducing a laser theodolite and a microcomputer. Both scattering and flickering of laser light have been solved by blowing clean air into the pilot pipe when necessary, and making full use of the computer programs capabilities.

(4) Others
Control of rolling, cutter layout taking into account the stability of the cutting face, reducing the soil inlet port, installation of a water-pressure sensor, increased hardness of the cutter tooth, and hard facing the cutter plate have also been added to the original system.

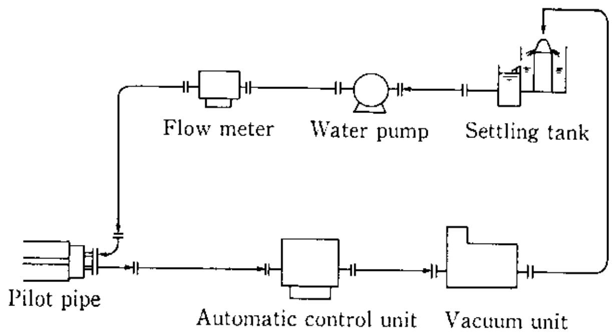



Fig. 2 Transportation loop for slurry used together with pump and vacuum unit

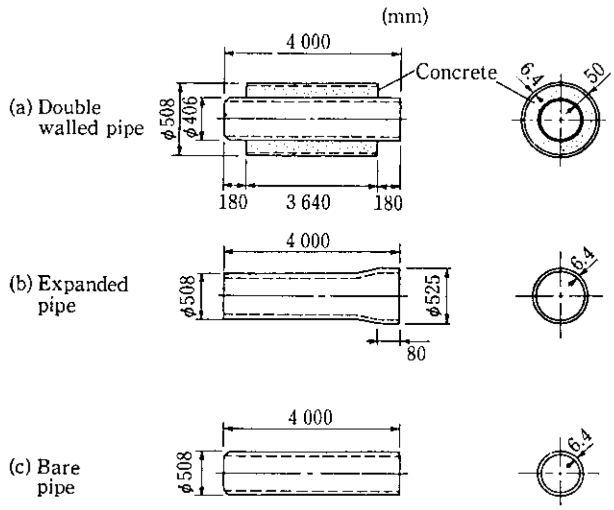



Fig. 3 Types of main pipe supplied for long span pipe jacking construction test

### 2.3 Suitable Pipe for Pipe Jacking Method

Three types of pipe were supplied for the field test as shown in **Fig. 3**. They were all mild steel, each 4 m in length, 508 mm outside diameter except for the inner pipe of double walled pipe and one side of the expanded pipe, and the wall thicknesses were 6.4 mm. The inner pipe of double walled pipe had 406 mm O.D. and 6.4 mm W.T. Double walled pipe was used as the transportation pipe, whereas both expanded pipe and bare pipe were provided as the casing pipe.

The double walled pipe consisted of both an inner and an outer pipe as shown in the figure, and the space between the pipes was filled with concrete.[2] Expanded pipe was produced by a mechanical expander, and bare pipe was uncoated.

The pipes were connected in the following manner: First, for double walled pipe, some steel segments were fitted around the welded joint[2] after two pieces of inner pipe are butt-welded. Second, for expanded pipe, one pipe was inserted into the other, and then circumferential fillet welding was performed. Bare pipes were also butt-welded, and the connected portion was kept uncovered.

## 3 Full-Scale Pipe-Laying Field Test

The demonstration test of long span pipe jacking method was conducted in Chiba Works of Kawasaki Steel. The site was at a corner of the West Plant. The soil is composed of fine sand reclaimed from the seabed with an $N$-value of about 10 down to GL $-5$ m, except near the surface of the ground, and mixed with innumerable small pieces of seashells. The groundwater level lies at about GL $-1.7$ m.

The proposed depth for pipe laying had an overburden thickness of about 2.15 m and the jacking distance was 200 m. The pipe arrangement is shown in **Fig. 4**, that is, in the order of double walled pipe, expanded pipe, and finally bare pipe. **Photo 2** shows the view of the main pipe jacking in the starting pit. In order to

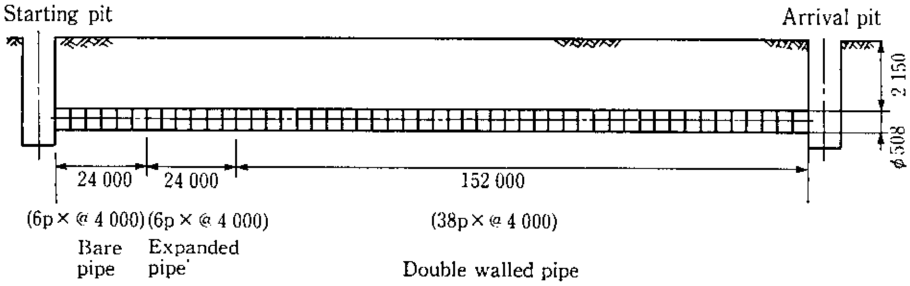



Fig. 4 Arrangement of main pipes below ground

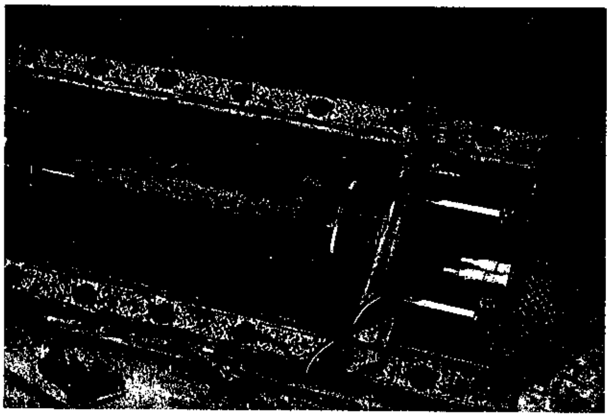


Photo 2 Closeup view of starting pit during main pipe jacking

decrease sliding frictional force, one-liquid friction reducing sliding material were prepared as a trial.

### 3.1 Buckling Strength of Steel Pipe

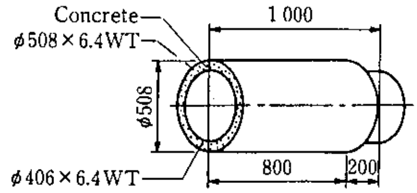
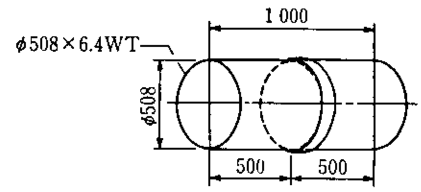
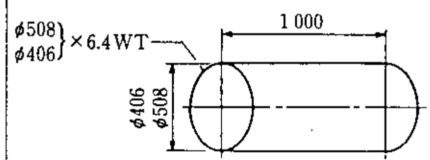
To clarify the buckling strength against the jacking force for the three types of pipe supplied prior to the field test, specimens shown in **Table 2**, were subjected to a compressive force along the centroidal axis of the pipe, using a 1 000-t structure testing machine. The results are shown in **Table 3**. Predicted values in the table show the critical buckling stress, which were estimated by Tetmajer's formula[3] multiplied by the cross sectional area of the pipe, and for expanded pipe, the strength reducing ratio to original pipe arising from plastic deformation was set to 0.2.

$$\sigma_{cr} = a - b\left(\frac{l}{r}\right)$$

where $a$ = 3 350 (constant)
$b$ = 6.2 (constant)
$\sigma_{cr}$: Critical buckling stress
$l$: Column length
$r$: Minimum radius of gyration of area

From Table 3, it is found that a good similarity exists between measured and calculated values for all pipes.

Table 2 List of buckling test specimens

| Type of pipe | Geometry (mm) | Number |
|---|---|---|
| Double walled pipe |  | 2 |
| Expanded pipe |  | 3 |
| Bare pipe |  | 3 (φ508)<br>3 (φ406) |

WT: Wall thickness

Table 3 Comparison of buckling prediction with test results

| Type of pipe | | Maximum load (tf) | | | Average (tf) | Pre-dicted*2 (tf) |
|---|---|---|---|---|---|---|
| | | TP1*1 | TP2*1 | TP3*1 | | |
| Double walled pipe | | 335 | 335 | — | 335 | 331 |
| Expanded pipe | | 260 | 261 | 262 | 261 | 267 |
| Bare pipe | φ508 | 327 | 328 | 329 | 328 | 334 |
| | φ406 | 324 | 326 | 327 | 326 | 331 |

*1 Test piece number
*2 These values are obtained by calculation

### 3.2 Jacking Force

The relationship between the jacking force and the

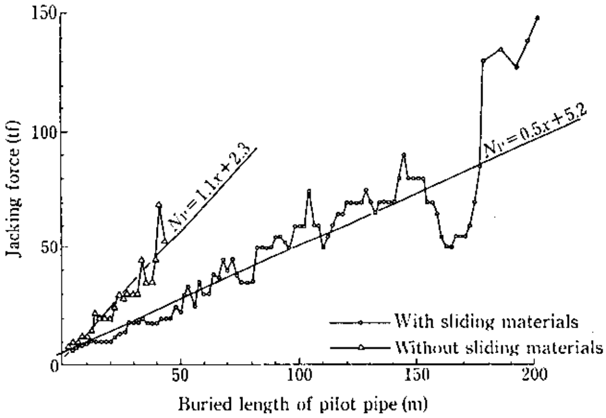



Fig. 5 Relationship between jacking force and buried length of pilot pipe

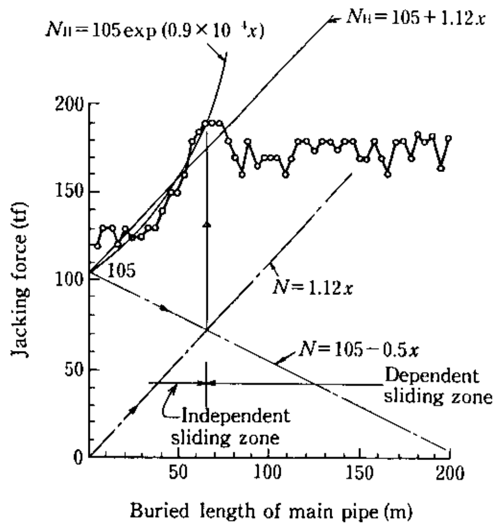



Fig. 6 Relationship between jacking force and buried length of main pipe

jacking distance during pilot pipe jacking is shown in **Fig. 5**; similarly, the relationship between the jacking force and the jacking distance during main pipe jacking is shown in **Fig. 6**. The following are observed from Fig. 5:

(1) In pilot pipe jacking, the jacking force was approximately proportional to the jacking distance.

(2) This relationship expressed by the method of least squares will be $N_P = 1.1x + 2.3$ without sliding materials, while $N_P = 0.5x + 5.2$ with sliding materials. Here $N_P$ denotes the jacking force and $x$ the jacking distance.

(3) From the relationship of (2) above, it is understood that the effect of sliding materials on the frictional force was so conspicuous as to reduce jacking force by half.

In the main pipe jacking shown in Fig. 6, on the other hand, the fluctuations have completely changed compared with the pilot pipe jacking in Fig. 5. Namely, the jacking force realizes a peak value at around 60 to 70 m, and there-after does not increase, even if the jacking distance becomes longer, and remains constant. These phenomena can be analysed as follows.

### 3.2.1 Independent sliding zone

This is an area where the jacking distance is up to 60 or 70 m. During main pipe jacking, the pilot pipe is quite far in front and the surrounding earth is compact. As a result, the main pipe cannot be inserted smoothly even if pushed vigorously, and it penetrates the ground gradually while receiving elastic deformation corresponding to the jacking force imposed.

In this case, the jacking force can be determined by referring to the schematic model shown in **Fig. 7** as follows:

The equilibrium of forces gives

$$dN_H = \pi(f_H D - f_P d)dx \quad \cdots\cdots (1)$$

where $N_H$: Jacking force of main pipe
$f_H$: Frictional resistance of main pipe
$f_P$: Frictional resistance of pilot pipe
$D$: Main pipe diameter
$d$: Pilot pipe diameter
$x$: Main pipe jacking distance

The distance the pilot pipe moves is minute compared with that of the main pipe, and the pilot pipe takes on a sliding movement. Consequently, Eq. (1) reduces to

$$dN_H = \pi f_H D dx \quad \cdots\cdots (2)$$

where $f_H$ is assumed to be proportional to the jacking force such that

$$f_H = sN_H \quad \cdots\cdots (3)$$

where $s$ is a coefficient of apparent-friction of soil. Substituting Eq. (3) into (2), Eq. (2) yields

$$dN_H = s\pi DN_H dx. \quad \cdots\cdots (4)$$

Equation (4) can be written

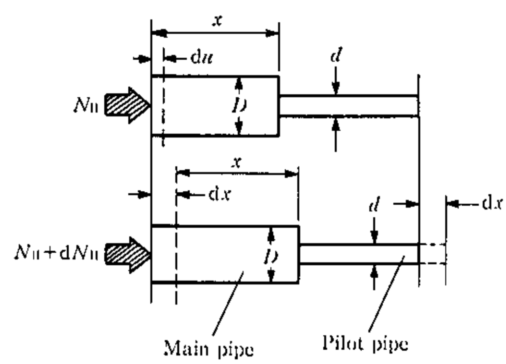



Fig. 7 Schematic model during main pipe jacking

$$\frac{dN_H}{N_H} = s\pi D dx \cdots\cdots(5)$$

in which

$$s\pi D = K_1. \cdots\cdots(6)$$

Integrating Eq. (5) over $x$, we have

$$N_H = e^{K_1 x + \alpha_1} = C_1 e^{K_1 x},$$

provided that $C_1 = e^{\alpha_1}$.

From the measured values, we obtain

$$\left.\begin{aligned} x = 0 \quad &: N_H = 105 \\ x = 6\,000 &: N_H = 180 \end{aligned}\right\} \cdots\cdots(7)$$

Substitution of the above gives

$$C_1 = 105, K_1 = 0.9 \times 10^{-4}.$$

Thus $N_H$ is given as

$$N_H = 105 \exp(0.9 \times 10^{-4} x). \cdots\cdots(8)$$

Next, from Eq. (6) we obtain

$$s = 5.6 \times 10^{-7}. \cdots\cdots(9)$$

Then from Eqs. (3) and (9), $f_H$ will be as follows:

$$f_H = sN_H = 5.6 \times 10^{-7} N_H \cdots\cdots(10)$$

Equation (10) will be as shown in **Fig. 8**, and indicates that as the jacking force of the main pipe increases, its frictional resistance also increases linearly, thereby making the equilibrium valid.

Compressive displacement in the pipe-axis direction at a jacking distance of, for instance, 60 m is written by

$$du = \frac{N_H}{AE} dx \cdots\cdots(11)$$

where $u$: Displacement

$A$: Area of cross section of main pipe

$E$: Young's modulus of steel pipe

Therefore

$$u = \frac{1}{AE}\int_0^{6\,000} 105 \exp(0.9 \times 10^{-4} x) dx \fallingdotseq 39 \text{ mm}.$$

This value approximates the deformation of the pipe

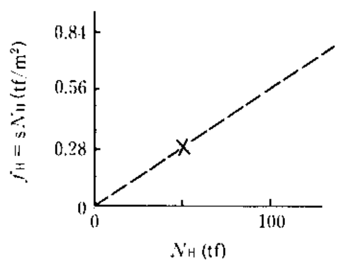



Fig. 8 Relationship between resistance at external surface and jacking force of main pipe

observed during main pipe jacking.

### 3.2.2 Dependent sliding zone

This is an area where the jacking distance exceeds 60 or 70 m. It is considered that in this case the main pipe and pilot pipe move simultaneously. Thus, the following assumption in Eq. (1),

$$\pi(f_H D - f_P d) = K_2 \cdots\cdots(12)$$

will give

$$dN_H = K_2 dx \cdots\cdots(13)$$

$$\therefore N_H = K_2 x + \alpha_2 \cdots\cdots(14)$$

where if we apply the measured data,

$$K_2 = 0, \quad \alpha_2 = 175$$

are obtained. Then, we obtain Eq. (15) from Eqs. (12) and (14).

$$\therefore \frac{f_H}{f_P} = \frac{d}{D} \fallingdotseq \frac{1}{2} \cdots\cdots(15)$$

The above equation is established by referring to the result of the above-mentioned Fig. 5 because the sliding materials are supplied only to the main pipe side, not to the pilot pipe during main pipe jacking. When frictional resistance is sought here, it turns out to be 0.7 t/m² with sliding material and double that, at 1.4 t/m² without sliding materials.

Next, if it is supposed that the maximum jacking force occurs at the location where the total frictional resistance of the main pipe comes to be equal to that or the pilot pipe, the following equation as shown in Fig. 6 is derived:

$$1.12x = 105 - 0.5x \cdots\cdots(16)$$

$$\therefore x = 65 \text{ m}$$

Thus the estimated value agrees with the measured. If the jacking force from Eq. (8) using the above value is obtained, it becomes $N_H \fallingdotseq 188$ t. On the other hand, if the following equation is used as a brief equation, we obtain

$$N_H = 1.12 \times 65 + 105 \fallingdotseq 178 \text{ t}.$$

Both the $N_H$ values reasonably approximate the measured values.

Here the generation point and the amount of maximum jacking force can be generalized using a brief equation, that is,

$$N_P = \pi f_P dL - \pi f_P dx \cdots\cdots(17)$$

$$N_H = k\pi f_P dx \cdots\cdots(18)$$

where $L$: Span length

$k$: Ratio of main pipe diameter to pilot pipe diameter

Since the maximum jacking force is yielded at the location where Eq. (17) is equal to Eq. (18),

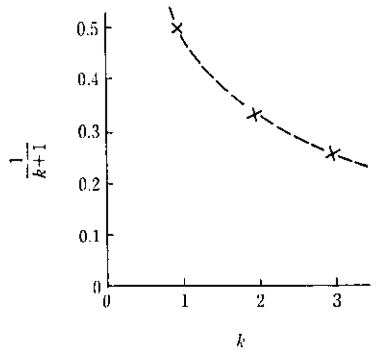



Fig. 9 Relationship between $1/(k+1)$ and main pipe diameter

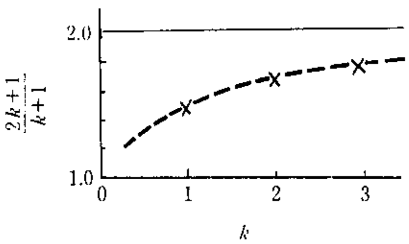



Fig. 10 Relationship between $(2k+1)/(k+1)$ and main pipe diameter

$$\pi f_P dL - \pi f_P dx = k\pi f_P dx$$

$$\pi f_P dx(k+1) = \pi f_P dL$$

$$\therefore x = \frac{1}{k+1} \times L \cdots\cdots\cdots\cdots\cdots\cdots\cdots (19)$$

Jacking force at this point can be conducted from Eq. (20):

$$N_{H\max} = \frac{2k+1}{k+1} \times N_{P\max} \cdots\cdots\cdots\cdots\cdots (20)$$

When coefficients $1/(k+1)$ and $(2k+1)/(k+1)$ on the right sides of Eqs. (19) and (20) are plotted against the main pipe diameter, **Figs. 9** and **10** are shown, and from these figures, the following can be explained.

(1) The generating position of maximum jacking force approaches the starting pit side along the curve shown in Fig. 9, as the main pipe diameter becomes larger.

(2) The maximum jacking force gradually increases as the main pipe diameter becomes larger, and becomes nearly twice as large as the maximum jacking force which is generated during pilot pipe jacking.

### 3.3 Jacking Accuracy

Jacking accuracy for the main pipe is shown in **Fig. 11**. A deviation of 37 mm to the left and 25 mm downward with respect to the target location was

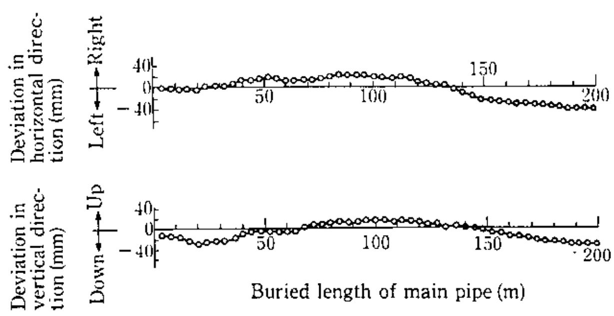



Fig. 11 Jacking accuracy for main pipe

observed. This indicates that in spite of the long distance, high-accuracy has been achieved. This is attributable to the fact that the new laser direction control devices have functioned effectively, and also to the spotting process which is able to accommodate the scattering of laser light and still-picture processing against the flickering phenomenon.

### 3.4 Propagation of Jacking Force

Propagation values of jacking force estimated from the strain gage attached to the interior of the pipe have been plotted against the jacking distance. The result is shown in **Fig. 12**. The jacking force decreases linearly toward the arrival pit along the main pipe due to frictional resistance between the pipe body and the surrounding soil.

When the frictional resistance of main pipe is derived from a falling gradient in the figure, it becomes 0.7 t/m$^2$ equal to the aforementioned value.

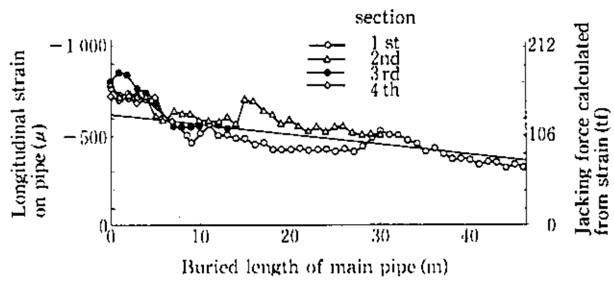



Fig. 12 Relationship between jacking force imposed and buried length of pipe

### 3.5 Cycle Time for Pipe Connection

When steel pipe is jacked, a series of operations are necessary for connecting the pipes, which depends on the types of pipe. **Table 4** shows the average cycle time measured in the field. Connection of double walled pipes takes the most time, since the steel segments must be fitted after the inner pipe is circumferentially-welded. It is considered that the difference between expanded pipe and bare pipe is mainly caused by the

Table 4 Cycle time for pipe connection operation

| Type of pipe | Procedure | Cycle time (min) |
|---|---|---|
| Double walled pipe | Pipe alignment→Tack welding→Girth welding→Coating of welded joint→Fitting up steel segment→Attaching steel piece | 70-90 |
| Expanded pipe | Pipe alignment→Inserting pipe→Tack welding→Girth welding | 60-80 |
| Bare pipe | Pipe alignment→Tack welding→Girth welding | 40-60 |

fact that in the case of bare pipe, only butt-welding is performed, whereas in the case of expanded pipe, fillet-welding with a specified leg length is required and, in addition, accurate insertion of one pipe into the other is essential.

## 4 Summary

The authors carried out a 200-m straight span underground pipe laying test employing 500-mm diameter pipe and the Komatsu Iron Mole, and clarified the following:

(1) To realize a long span pipe jacking method, the jacking force was increased, the slurry discharge function was reinforced, and the direction control device was improved, thereby successfully completing a 200-m straight line.

(2) Buckling strength for double walled pipe and bare pipe was approximated using the critical value estimated by Tetmajer's formula. If the strength reducing ratio for original pipe arising from plastic deformation of expanded pipe is set to 0.2, there is a good agreement between measured and calculated values.

(3) Jacking force during pilot pipe jacking is proportional to the jacking distance. In the present process, it is understood that the effect of sliding materials on the frictional force is so effective that it can reduce jacking force by half. On the other hand, during main pipe jacking, the jacking force must be analyzed in two separate zones. In the independent sliding zone where the main pipe and the pilot pipe move separately, jacking force is represented by a curve formula, whereas in the dependent sliding zone where the main pipe and the pilot pipe move simultaneoulsy, the jacking force is provided by a linear formula.

(4) Maximum jacking force is generated at the location where the total friction resistance of the main pipe is equal to that of the pilot pipe.

(5) The generating position of maximum jacking force gradually draws near to the starting pit side as the main pipe diameter becomes larger. Furthermore, the value of maximum jacking force gradually increases as the main pipe diameter increases, and becomes nearly twice as large as the maximum jacking force which occurs during pilot pipe jacking.

(6) Jacking accuracy of within $\pm 40$ mm in the vertical direction as well as in the horizontal direction have been achieved.

(7) Jacking force decreases linearly toward the arrival pit along the main pipe due to frictional resistance.

(8) Cycle time for pipe connection operation depending on the types of pipe is 70 to 90 min for double walled pipe, 40 to 60 min for bare pipe, and expanded pipe lies in between.

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