Structural Eng./Earthquake Eng., JSCE, Vol.13, No.2, 149s—161s, 1996 October

MODEL FOR STEERING A TUNNELING SHIELD UNDER VARYING GROUND CONDITIONS AND THE APPLICATION

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Creating a model for the behavior of a tunneling shield machine during subsurface propulsion is important for steering the shield. The authors predicted the behavior of the shield machine using an autoregressive series used for time series data; the physical relationship between eccentric moment and the change in the heading of the shield were modeled regressively. It was found that-from a study of the relationship between ground conditions and the parameter identification results of both the model for predicting behavior and the model for steering, based on the measured results of shield behavior under varying conditions, propulsion behavior and control amount correlate well with the ground conditions.

Key Words *:driving shields, ground condition, feedback prediction control, modelling, Kalman filtering theory*

1. INTRODUCTION

When guiding a tunneling shield, it is necessary to determine the deviation from the planned route by means of surveying, and to steer the shield so as to eliminate this deviation. The common method of steering is to use uneven shield jacks and generate eccentric moment. At curves, copy cutters are often used to excavate overbreak and forcefully guide the shield back to the planned route. Lately shield hulls are being partitioned, sometimes several times, to become articulated, thus improving the excavation performance and accuracy in curves. In such systems, adjusting the articulation angle becomes an important control factor[1]. However, as only the eccentric moment, effected by the jacking pattern, can be controlled in real time, this paper considers only the behavior of a shield machine receiving eccentric moment supplied by the jacking pattern. Behavior due to other factors will not be considered here.

For actual problems, such as steering a shield, the system in question must be modeled. Simultaneously, pursuance of a model true to reality will lead to complexity, and pursuance of an easily operable model will lead to simplicity-therefore the model will basically have to be an optimal combination of both complexity and simplicity.

There are two ways of constructing a model suited to the objective[2]. One is a physical or mechanical model, in which the internal structure of the system is established by means of theoretical reasoning. The other is for cases in which, owing to the large scale and complexity of the system's structure, a theoretical approach is impossible because the underlying theory is unknown. Here the system is interpreted as a black box, and a statistical model is created based solely on the relationship between input and output[3].

Based on the above concept of modeling, the system in question should be divided into a simple model for predicting the behavior of a shield machine, and a model for steering the shield machine when eccentric moment is applied. The authors predicted the behavior of the shield using an autoregressive model used for time series data[4], and, regarding steering, modeled the direction change of the shield due to eccentric moment using the

This paper is translated into English from the Japanese paper, which originally appeared on J. Struct. Mech. Earthquake Eng., JSCE, No.451 / I-22, pp.139-148, 1993.1.

physical relationship[5]. In actuality, as the parameters of both models had to be revised according to measurement data obtained intermittently, the data was input sequentially, and the Kalman filtering theory, a modern control theory which can revise the optimum estimated values in order[6)-9)], was applied, resulting in higher speed and accuracy. As a consequence, identification and control could be carried out simultaneously, resulting in a system with adaptable steering, i.e. one in which steering performance can be revised continuously[10)-12)].

Both models are not necessarily accurate deterministically, but are being used for control in actual work without problems. This stems from the assumption that prediction and control are repeatedly carried out within short periods of time-for repetitive use in short intervals the models can perform adequately even if they are not complex. For such reasons, no model based on measurements of actual behavior has been evaluated to date, and little work has been done on modeling. As in actuality already a large number of precedents exist for the automated steering of shield machines, it should be possible to study modeling from the standpoint of soil mechanics.

Hence in this paper the applicability of a model for predicting shield behavior and a model for steering the shield were evaluated, based on measurements of shield behavior during work under differing ground conditions. Additionally, the system's parameters as well as ground conditions were identified and compared.

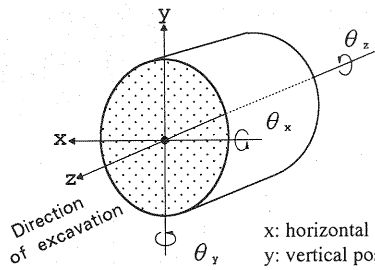
The result was that shield behavior could be predicted with satisfactory accuracy using an autoregressive model based on data obtained from intermittent measurements. The progress of the behavior correlated extremely well with the N value and modulus of deformation of the ground at the tunneling face.

Also regarding the behavior of the shield when reacting under eccentric moment supplied by the jacking pattern, the eccentric moment and the amount of direction change correlated well with the N value and modulus of deformation of the ground at the tunneling face.

2. WORK CONDITIONS

(1) Field Measurements

The measurements on automated shield control used were those from relatively small–bore work carried out after 1986. Data from six sites with as diverse ground conditions as possible were gathered. The shield machine's position and attitude were comprised of six components, as shown in



x: horizontal positional deviation
y: vertical positional deviation
z: excavated distance
θ_x : pitching
θ_y : yawing
θ_z : rolling

Figure 1 Shield Machine Position and Attitude

Figure 1, and during automated control all of these must be measured.

Horizontal deviation was calculated by multiplying the angular change (found by gyrocompass) by the distance excavated (found using the jacking–stroke meter). Vertical deviation was measured using a differential–pressure settlement gauge. The resolution of the gyrocompass was 0.01 degrees, that of the jacking–stroke–meter 1 mm, and that of the differential–pressure settlement gauge 0.5 mm. Pitching and rolling were measured using a gravitational accelerometer, which had a resolution of 0.05 degrees.

(2) Ground Conditions

Site conditions are shown in **Table 1**. Measurements were carried out once for every 5 cm of driving. The control system could be applied regardless of whether alignment was straight or curved, but in the curves many factors other than jacking pattern also contribute to the control of direction. As this paper is concerned only with steering by means of regulating the jacking pattern, the measurements pertaining to curves were set aside, even though measurements were carried out for the entire route; hence only measurements for straight alignment sections were included in the material for the study.

Figure 2 shows a borehole log for the sections where the shield machine was steered. The borehole logs were accepted as being typical extracts from the section measured.

3. PREDICTION OF SHIELD POSITION

(1) The Need for Prediction

When handling a complex, large–scale system such as the behavior of a tunneling shield, it is important that an efficient control system is

Table 1 Field Measurement Sites

Measurement Site			A	B	C	D	E	F
Tunnel Purpose			Sewerage (wastewater trunk sewer)	Sewerage (wastewater trunk sewer)	Sewerage (runoff trunk sewer)	Sewerage (wastewater trunk sewer)	Sewerage (wastewater trunk sewer)	Water-Supply
Tunneling Machine	Type of Shield Machine		EPB	EPB	EPB	EPB	EPB	Slurry
	Articulation		Yes	Yes	Yes	Yes	No	No
	No. of Jacks		12	12	8	8	8	8
Section	Tunneling Shield	(mm)	3,680	3,080	2,280	2,130	2,130	2,130
	Tunneling Shield	(mm)	5,175	4,990	4,305	4,050	4,000	4,080
	Liner Segment	(mm)	3,550	2,950	2,150	2,000	2,000	2,000
	Liner Segment	(mm)	3,250	2,700	1,844	1,844	1,844	1,850
Alignment	Length	(m)	877.3	851.1	868.9	899.9	895.2	1207.0
	Grade	(‰)	− 1.20	− 1.00	− 1.30	− 5.00	− 1.40	24.47

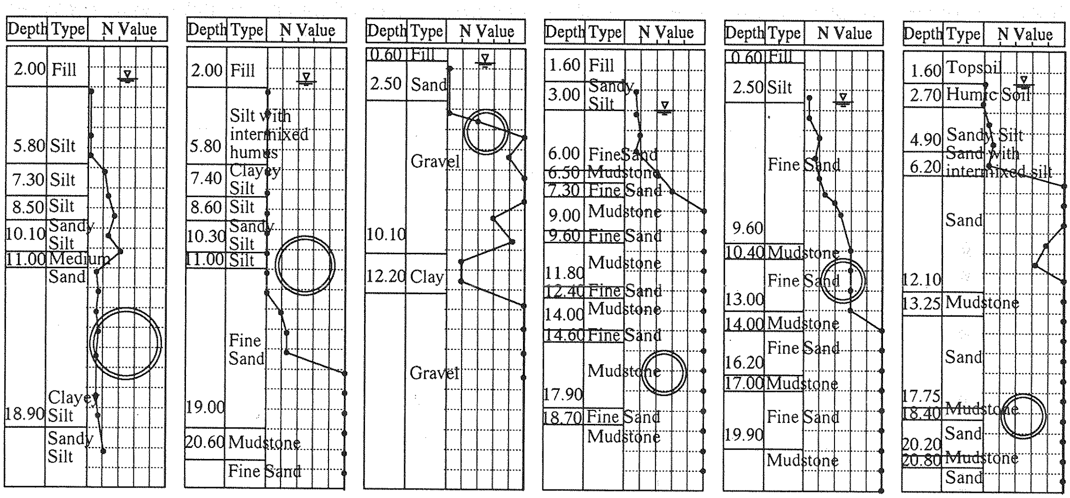
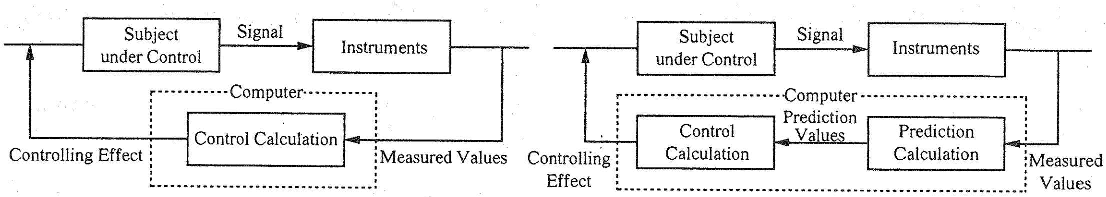


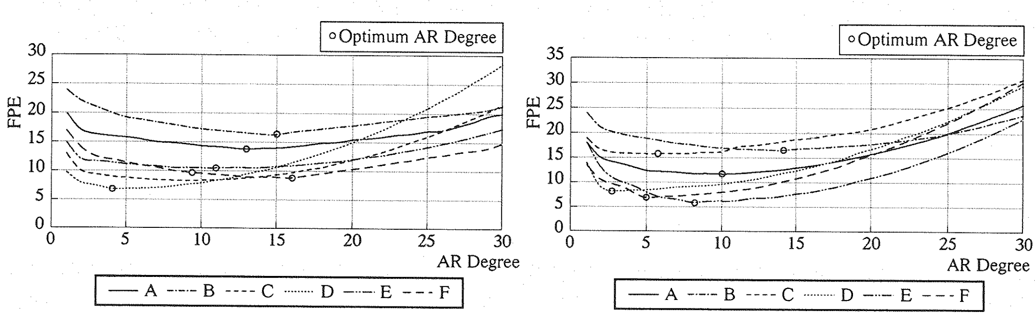
Figure 2 Ground Conditions under whitch Shield Machine Behavior was Measured



(a) Feedback Control

(b) Feedback–Prediction Control

Figure 3 Control Schema



(a) Horizontal Deviation FPE

(b) Vertical Deviation FPE

Figure 4 FPE Calculation Results

designed. The highly stable feedback control system is effective for automatically guiding a shield machine using steering based on measurement results, even in conditions of disturbance. Feedback control has the disadvantage, however, of inevitably being late in responding to changes in the goal values. Additionally, in reality, as a considerable amount of time is required until the steering calculations based on measurement values are carried out and the actual action is put into effect to correct route alignment, in many cases the steering process cannot keep up with the advance of the shield, and only the shield's position and attitude are obtained in real time.

Hence predicting the shield's position and attitude quantitatively will allow steering to be carried out based on predictions, and delays in steering can be eliminated by factoring the time until the action is carried out, thereby simplifying the control process. This type of control is referred to as "feedback–prediction" control; the prediction of the shield machine's behavior is a prerequisite for improving the alignment of shield–driven tunnels.

Figure 3 shows a schematic diagram of the basic computer system.

(2) Prediction Model

It was decided to divide the deviation from the planned alignment into horizontal and vertical coordinates, to handle these as time series data with the excavation time as the time axis, and to carry out the predictions statistically.

The mathematical model used for statistical prediction was the AR (autoregressive) model, the basic equations of which are expressed as follows:

$$x_t=\sum_{i=1}^{F}\alpha_i \cdot x_{t-} \quad (1)$$

$$y_t=\sum_{i=1}^{F}\beta_i \cdot y_{t-i} \quad (2)$$

where $x_t(y_t)$ is the horizontal (vertical) deviation from the planned route for distance excavated t (in mm), $a_i(b_i)$ is the horizontal (vertical) AR factor, and F is the degree of the autoregressive model.

(3) Optimum AR Degree and Ground Conditions

In applying the autoregressive model, it is necessary to select its optimum degree. A commonly employed technique for determining the degree is the practical FPE (Final Prediction Error) minimization technique, suggested by Akaike[13]. Hence, in order to find the optimum AR degree for the project discussed in this paper, FPE calculations were carried out separately for horizontal and vertical deviation, as shown in **Figure 4**.

At all of the sites, the FPE in the vertical direction was larger than in the horizontal direction, although the optimum AR degree was smaller in the vertical direction. This is thought to be because the behavior in the vertical direction was characterized by finer movement than that in the horizontal direction, requiring a larger number of changes to be carried out by altering the jacking pattern. This is understandable when considering that most of the work was for wastewater systems, which place stringent demands on controlling elevation.

The FPE distribution for the AR degree is naturally smallest for the optimum AR degree, but the FPE calculation results do not vary a great deal at degree values near the optimum AR degree. This indicates that selecting a degree close to the optimum AR degree does not affect the accuracy of the prediction significantly.

As the optimum AR degree which minimizes the FPE expresses the behavioral change of the shield machine's locational deviation with the greatest accuracy, it was decided to compare the optimum AR degree with ground conditions at the six sites where work was actually carried out.

The soil classification constants used in order to study the deviation under different ground conditions are shown in **Table 2**. The values were obtained as follows: The N value given is the mean of the N values from the crest to the invert at the tunneling face; the overburden and lateral pressure at rest are for the center of the tunneling face; the modulus of deformation was determined by triaxial compression test for silt and mud, and by applying the N values to the Schultze–Menzenbach equation for sand and gravel (for which there are no triaxial compression test results).

Figure 5 shows the relationships between the optimum AR degree and the soil constants.

a) N value and Optimum AR Degree

A linear least–squares approximation of the relationship between the N value and optimum AR degree results in the following equations:

$F_x=-0.195 \bullet N+15.1$

(coefficient of correlation r=–0.96)

$F_y=-0.178 \bullet N+12.6$

(coefficient of correlation r=–0.93)

where $F_x(F_y)$ is the optimum horizontal (vertical) AR degree, and N is the N value.

The correlation between the N value and the optimum AR degree shows that the optimum AR value becomes smaller as the N value becomes larger, for both horizontal and vertical deviation. The coefficient of correlation indicates a clear

Table 2 Soil Constants

Measurement Site	A	B	C	D	E	F
Overall Soil Type	Silt	Silt	Gravel	Mudstone	Sand	Sand & Mudstone
Overall N Value	6	2	30	50以上	30~50	50以上
Overburden Pressure[1)] (tf/m²)	24.26	17.48	7.74	30.02	20.4	31.8
Lateral Earth Pressure at Rest[2)] (tf/m²)	22.15	12.96	5.37	22.25	13.07	22.8
Active Earth Pressure[3)] (tf/m²)	14.87	8.76	4.72		11.48	
Passive Earth Pressure[4)] (tf/m²)	35.44	32.29	18.88	181.35	61.43	135.42
Modulus of Deformation[5)] (kgf/cm²)	73.0	23.6	353.0	5000.0	218.0	2632.0

※ 1):Combined effective earth pressure and water pressure
※ 2):Jarky's formula was used to calculate the coefficient of static earth pressure, considering earth and water pressure combined for clayey soil and separate for sandy soil.
※ 3):Rankine–Resal equation
※ 4):Rankine–Resal equation
※ 5):Triaxial compression test (silt, mudstone) and the Schultze–Menzenbach formula (sand, gravel) were used. In alternations layer thickness was factored to produce an average value.

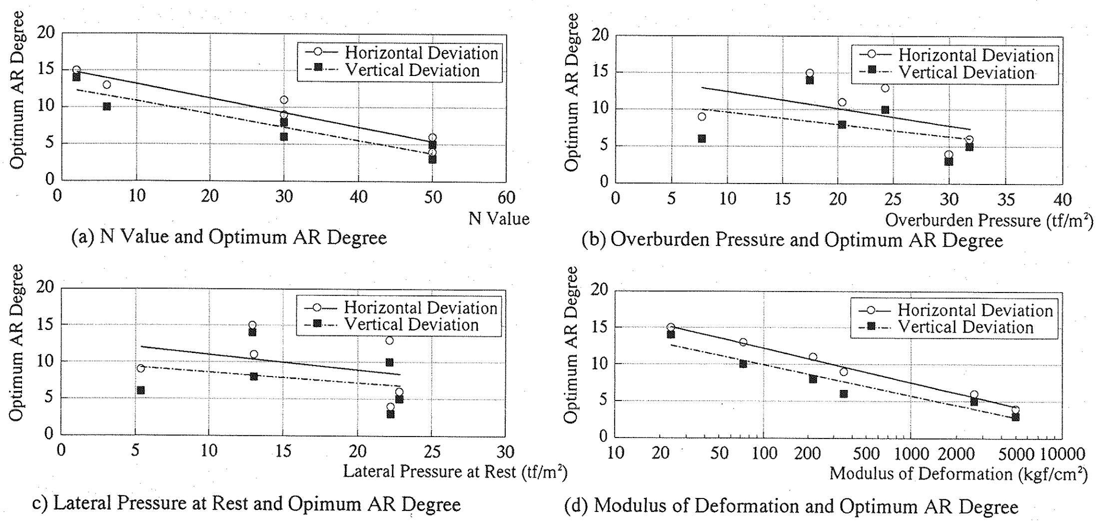


Figure 5 Ground Conditions and Optimum AR Degree

correlation. This is surmised to be due to the low N values and the consequently smooth movement of the shield.

b) Overburden Pressure and Optimum AR Degree

A linear least–squares approximation of the relationship between the overburden pressure P_v (tonf/m²) results in the following equations:

$F_x=-0.231 \cdot P_V+14.7$

(coefficient of correlation r=–0.49)

$F_y=-0.163 \cdot P_V+11.2$

(coefficient of correlation r=–0.37)

In the relationship between overburden pressure and optimal AR degree, a slight correlation exists; for an increase in the overburden pressure and lateral pressure at rest, there is a corresponding decrease in the optimum AR degree. However, correlational analysis shows the coefficient of correlation to be small, and it is clear that it cannot be evaluated quantitatively.

c) Lateral Pressure at Rest and Optimum AR Degree

A linear least–squares approximation of the relationship between lateral pressure at rest P_o (tonf/m²) and the optimum AR degree results in the following equations:

$F_x=-0.209 \cdot P_0+13.1$

(coefficient of correlation r=–0.36)

$F_y=-0.140 \cdot P_0+10.0$

(coefficient of correlation r=–0.25)

The relationship between lateral pressure at rest and optimum AR degree, as is the case with overburden pressure, cannot be evaluated quantitatively.

d) Modulus of Deformation and Optimum AR Degree

A linear least–squares approximation of the relationship between the modulus of deformation E_s (kgf/cm²) and optimum AR degree results in the following equations:

$F_x=-4.66 \cdot \log E_S+21.5$

(coefficient of correlation r=–0.99)

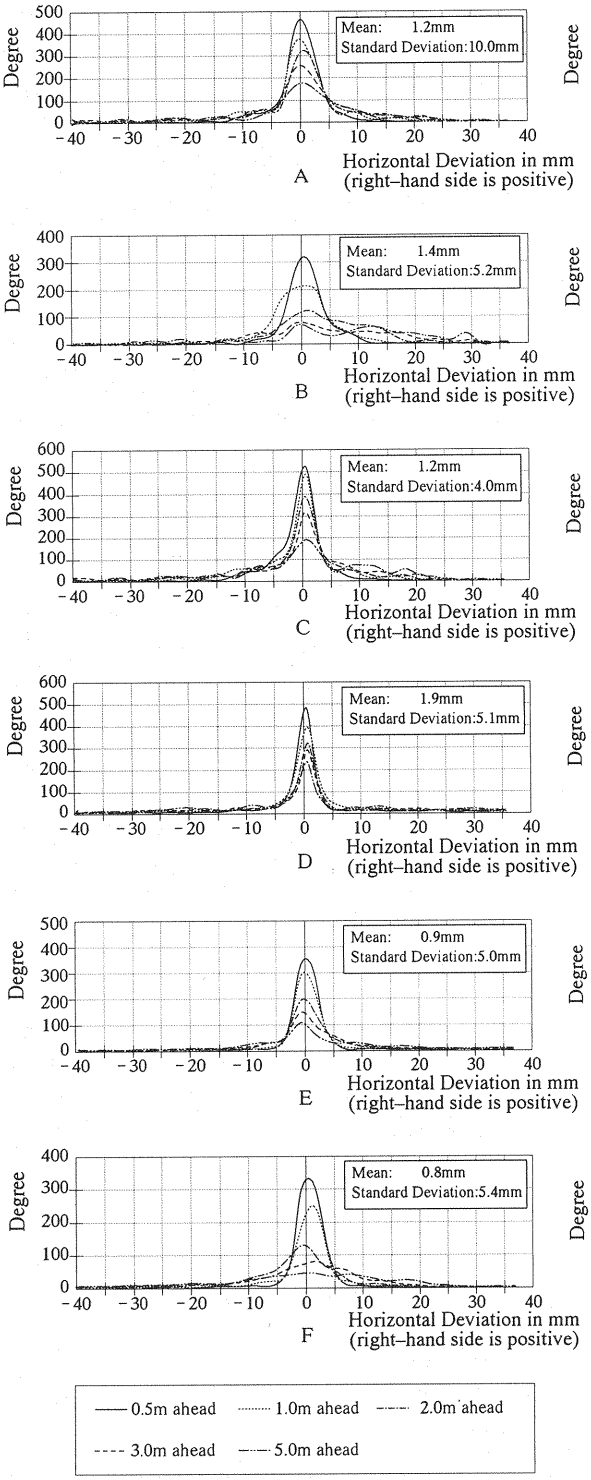


Figure 6 Distribution of Horizontal Deviation Prediction Error

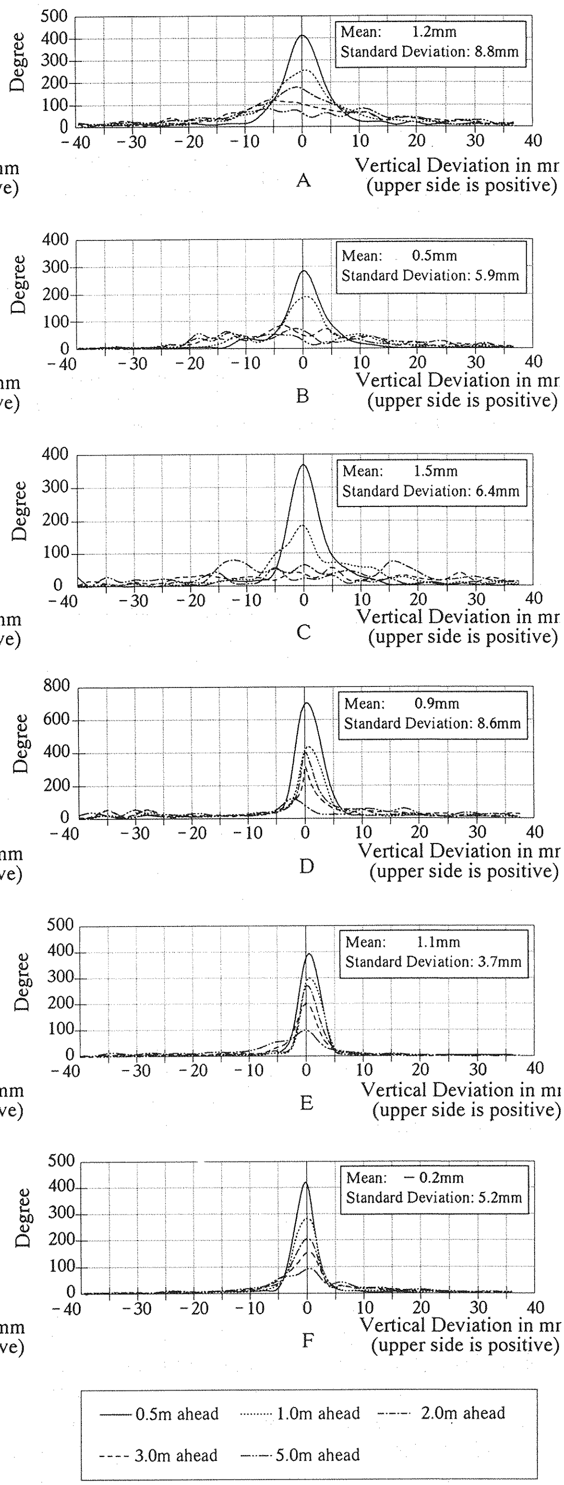


Figure 7 Distribution of Vertical Deviation Prediction Error

$F_y = -4.22 \cdot \log E_s + 18.4$

(coefficient of correlation $r = -0.96$)

The relationship between the modulus of deformation and the optimum AR degree was plotted on a semi–logarithmic graph. The correlation was exceptionally good, and it is evident that the AR degree becomes smaller as the modulus of deformation increases.

From such results, it is clear that the behavior of shield machine is not dependent on the stress in the ground, but is instead determined by soil constants expressing the hardness of the soil, such as the ground's modulus of deformation and N value. Therefore, it is better to explain differences in shield machine behavior in different types of ground not by the plasticity of the ground, but by its elasticity. In actual steering operations, the AR degree must be selected in advance; we believe it has been shown that there are no problems with making the selection based on the N value or modulus of deformation.

Note, however, that there are also many other factors which can affect the behavior of a shield machine, such as excavation conditions (i.e. jacking pressure and jacking speed) or the stability of the tunneling face. These have not been considered in this study, and will in future have to be systematically taken into account based on extensive measurement data.

(4) Prediction Error

When using an autoregressive model for predicting locational deviation of the shield machine, it is necessary to select the degree of the optimum autoregressive model. However, as the optimum AR factor cannot be found in advance, the predictions carried out at each site used an autoregressive model ranging up to 10. The future positions after 0.5, 1, 2, and 3 m were predicted using the autoregressive model, based on the horizontal and vertical deviation at the six sites where measurements were carried out. The deviation between the predictions and the actual positions the shield machines arrived was taken as the prediction error. As presenting the prediction error according to distance excavated would result in a huge amount of data, the prediction error at each site was organized according to frequency at intervals of 2.5 mm and compared. Frequency distributions are usually expressed in histograms, but as these do not allow juxtapositions, the histogram ceilings were connected by a spline function, as shown in **Figures 6** and **7**. For the prediction error for 0.5 m ahead shown in the figures, the data quantity, mean, and standard deviation are also shown.

For all data, the width of the prediction error distribution becomes smaller as the distance to the location being predicted becomes shorter. Prediction error for 0.5 m ahead was almost 0 mm on average, and standard deviation was also small. As in actual work the predictions carried out to correct control delays in steering are carried out for 5 cm ahead, the prediction method can be said to be valid.

Observations of the prediction error distribution of each site show that the prediction accuracy at sites in stable ground (sites D, E, and F) was greater than at sites in weak ground (sites A and B).

(5) Identified AR Factor

When using an AR model for predicting the positional deviation of shield machines, it is important to carry out an identification of the optimum AR factor based on measured data. This is where Kalman filtering theory comes in; it is used to successively identify the AR factor speedily and accurately, using measurement data obtained intermittently. The identified AR factor would result in a huge amount of data if given according to distance excavated; hence the AR factor at each site was organized according to frequency and compared. As with prediction error, the ceilings of the histogram frequency–processed results were connected by a spline function, as shown in **Figures 8** and **9**.

As for the prediction error, the AR model used was to the 10th degree. As the AR factors from the 6th to the 10th degree varied greatly and were not valid as quantitative material, however, and owing to constrictions of space, these were omitted, and only the AR factors from the 1st to the 5th degree are given herein.

The mean AR factor of the 1st degree was small at sites A and B, where the optimum AR degree was high. In turn, at sites D, E, and F, where the optimum AR degree was low, the mean value of the 1st AR degree was low. This corresponds to the ground at sites A and B being weak, and stable at sites D, E, and F.

4. STEERING THE SHIELD MACHINE

(1) Steering

When predicting the position of the shield machine, the autoregressive model-which relies solely on the relationship between input and output-was used, but when controlling the position of a shield machine, it is necessary to guide the shield based on a formula which takes into account the state of the shield jacks and the physical appearance of the shield's locational deviation. It is impossible to directly tie the departure from planned shield direction to moment occurring due to jacking

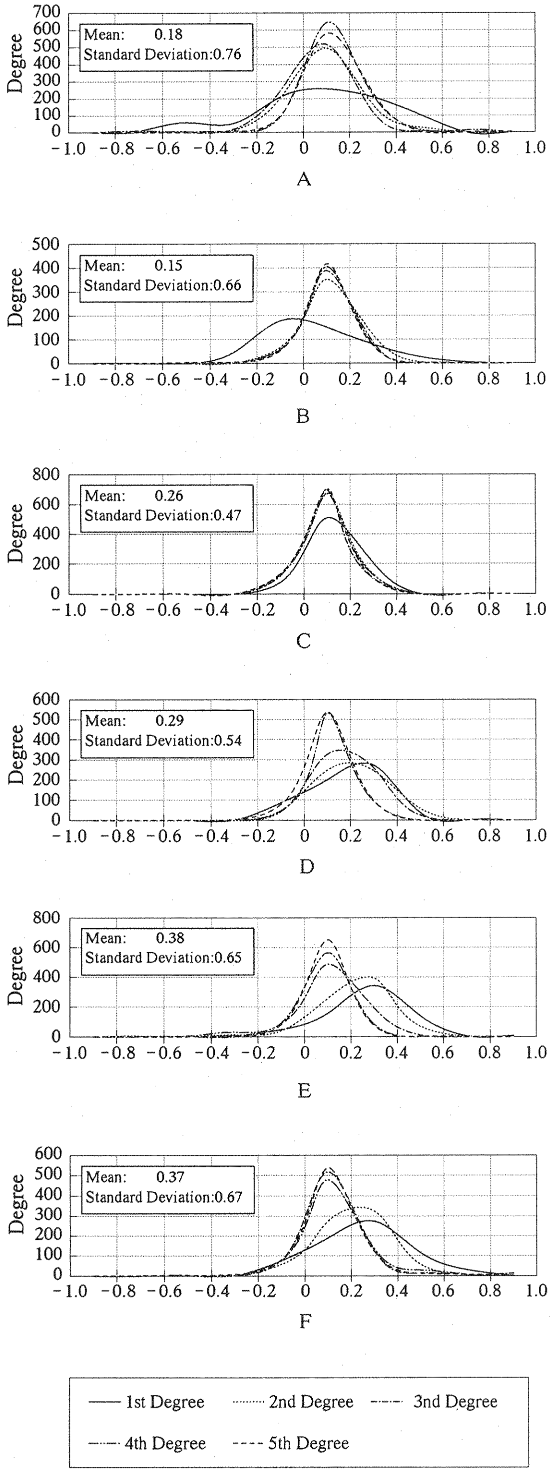


Figure 8 Distribution of Identified AR Factor (Horizontal)

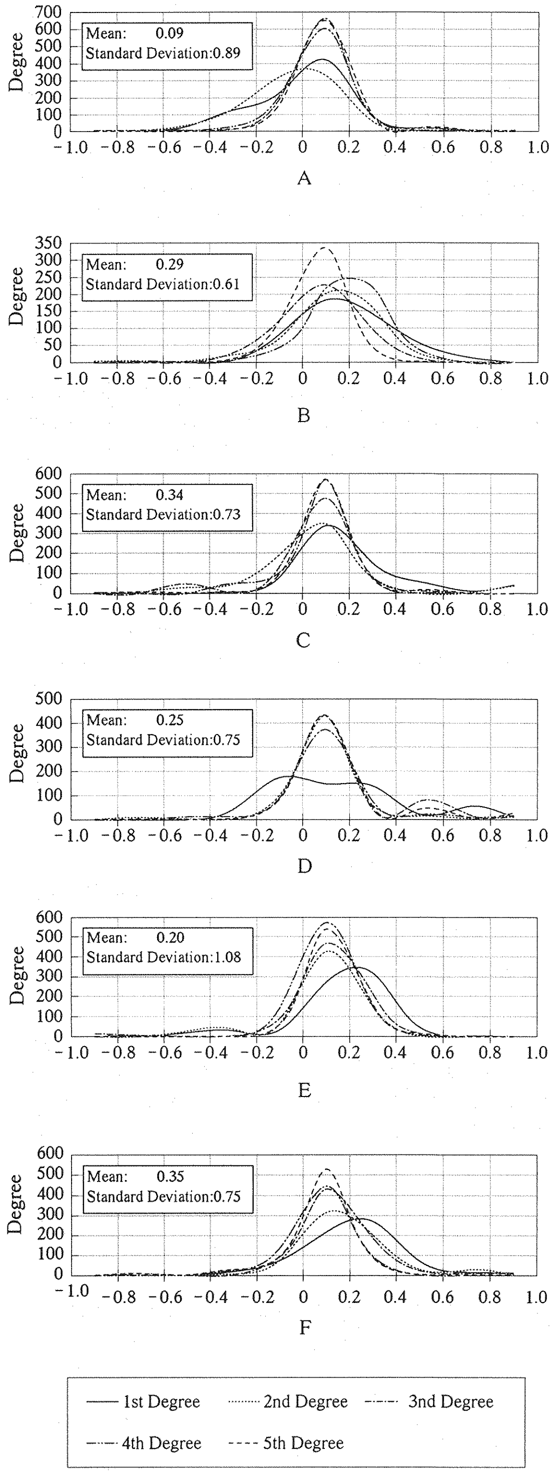


Figure 9 Distribution of Identified AR Factor (Vertical)

strokes, jacking pressure, or copy cutters. Hence the rate of direction change-differentiated by distance excavated with the departure from the planned direction-was used as observation data.

Although the eccentric moment is a quantity required for the control of the shield machine's position, it cannot be observed. Therefore the eccentric moment will be linked to the jacking pattern, and the observed jacking pattern will be used as the amount of control.

In practice, once the eccentric moment to be controlled is obtained, the jacking pattern suited to that eccentric moment can be found.

(2) Control Model

The shield machine's rate of direction change from the planned direction according to the distance excavated-considered to be in proportion to the moment acting on the shield machine-is expressed as follows, if the relationship is divided into horizontal and vertical components:

$$\frac{d\theta_t}{dt} \propto M_x \qquad (3)$$

$$\frac{d\phi_t}{dt} \propto M_y \qquad (4)$$

where θ_t (ϕ_t) is the shield machine's departure from horizontal (vertical) planned direction (in degree), t is the distance excavated (in m), and M_x (M_y) is the eccentric moment in the horizontal (vertical) direction (in tonf•m)

Next, the jacking pattern is converted into a physical quantity, and its relationship with the eccentric moment is considered. Note that in order to convert the jacking pattern into eccentric moment, eccentric moment must be considered to be at or near the center of figure of the shield machine. In other words, the distance from the shield's center of figure to the jack's contact point multiplied by the thrust of each jack comprises, collectively, the eccentric force. However, the ground through which the shield machines are tunneling are weak and heterogeneous, and each jack has its own peculiarities; therefore the shield machine was considered as a whole. Consequently, the rate of direction change and the converted coefficient of eccentric moment were considered as being comprehensive and applicable to the center of figure of the shield machine. Additionally, the shield machine underwent a certain amount of rolling at all times, and the coordinates for the points at which the jacks act must take into account this rolling.

The jacking pattern is shown in **Figure 10**.

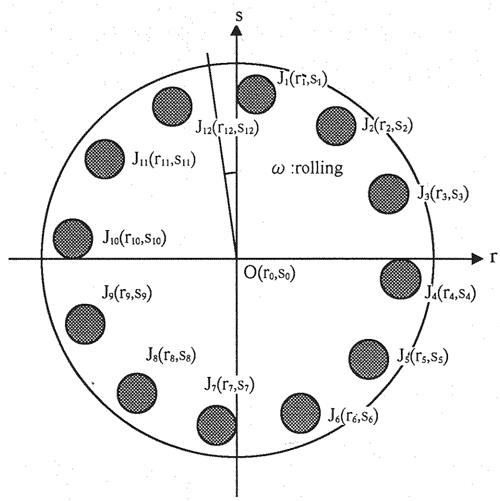


Figure 10 The Shield Machine Jacking Pattern

The moment on the jacks from center of figure O is expressed by the following equations:

$$M_x = \sum_{i=1}^{m} \frac{P}{n} \cdot (r_i - r_0) \cdot S_i \qquad (5)$$

$$M_y = \sum_{i=1}^{m} \frac{P}{n} \cdot (s_i - s_0) \cdot S_i \qquad (6)$$

where m is the total number of jacks used, n is the number of jacks used, $O(r_0 , s_0)$ are the coordinates of the center of figure (in m), P is the total thrust (in tonf), $J_i(r_i , s_i)$ are the coordinates of the points at which the jacks act, and S_i is the state of the jacks (1 when in use, 0 when not in use).

From the above, the shield machine's rate of direction change is linked to eccentric moment-found using conversion coefficients determined for each jack, and from observed hydraulic pressure and jacking pattern-and is expressed by Equations 7 and 8, based on Equations 5 and 6.

$$a_t = K_x \cdot M_x \qquad (7)$$

$$b_t = K_y \cdot M_y \qquad (8)$$

where α_t(β_t) is the rate of change in the horizontal (vertical) direction (in degree/m), and K_x (K_y) is the rate of direction change and moment conversion coefficient (in degree/tonf•m/m).

(3) Calculation of the Optimum Control Amount for the Shield Machine

The amount of control is determined by first

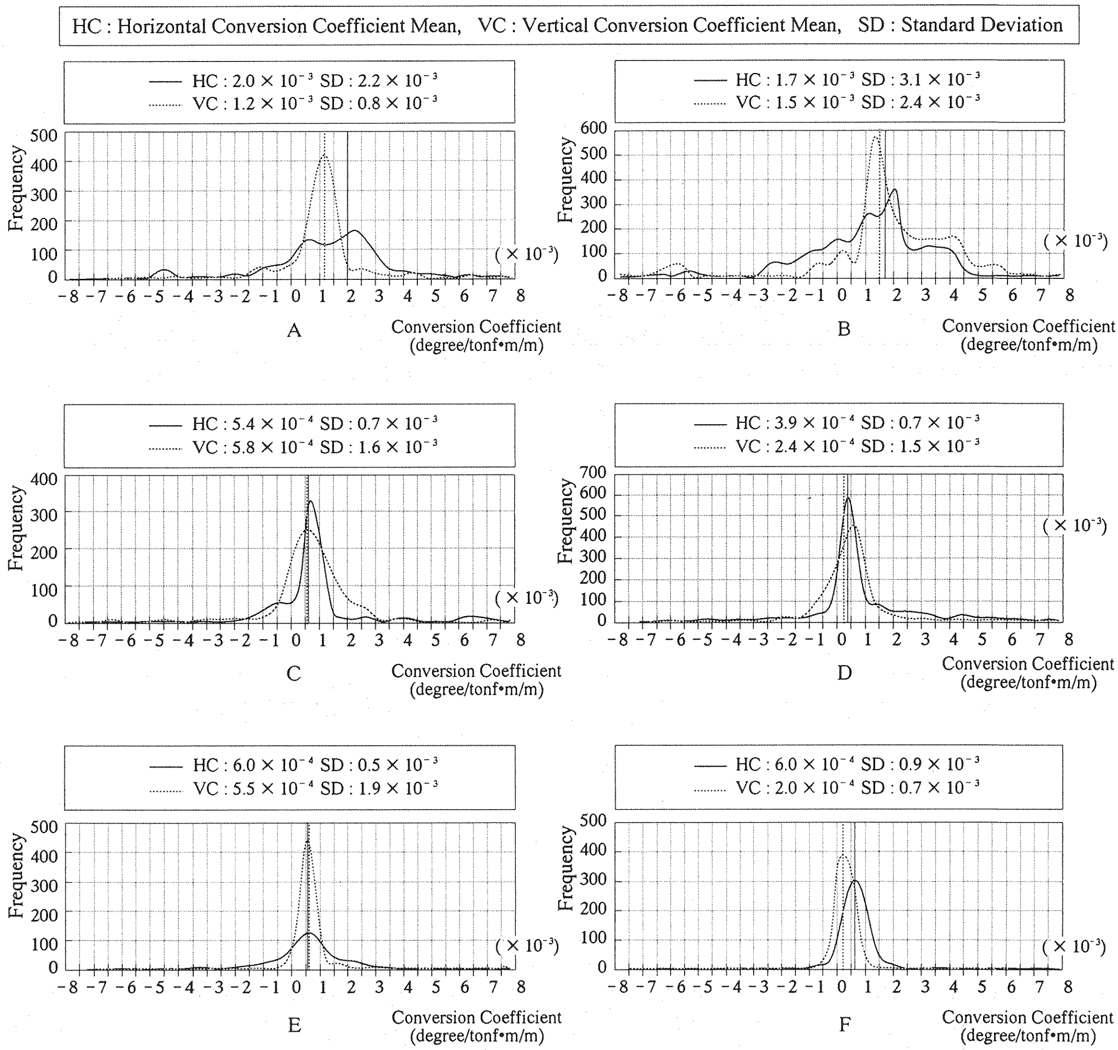


Figure 11 Distributions of Conversion Coefficient

calculating the eccentric moment of the correction, using the direction change required to reach the preset intended location, as well as the optimum conversion coefficient obtained successively by Kalman filtering. An optimum jacking pattern suiting this eccentric moment is then found.

The current direction change of the shield is (θ_t, ϕ_t), the direction change of the shield at the goal, ahead of the abrasion point j is (θ_{t+j} , ϕ_{t+j}), and the measurement interval is Δ t. At that point, the rate of direction change in regard to the distance excavated is-assuming that the change is constant-as shown in Equations 9 and 10.

$$a_{t+j}=\frac{\theta_{t+j}-\theta_t}{j\cdot\Delta t} \tag{9}$$

$$b_{t+j}=\frac{\phi_{t+j}-\phi_t}{j\cdot\Delta t} \tag{10}$$

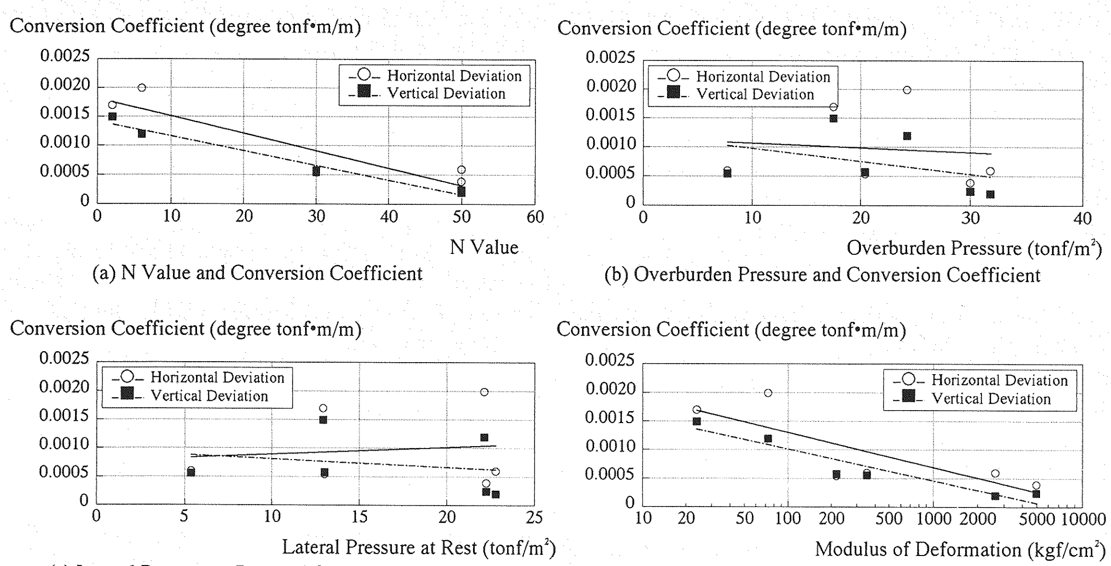
Here the rate of direction change to be controlled is, based on Equations 9 and 10, expressed only by known quantities, as follows:

$$K_x\cdot M_x=a_{t+j}=\frac{\theta_{t+j}-\theta_t}{j\cdot\Delta t} \tag{11}$$

$$K_y\cdot M_y=b_{t+j}=\frac{\phi_{t+j}-\phi_t}{j\cdot\Delta t} \tag{12}$$

Next, using the obtained direction change of the shield, an optimum jacking pattern is found. The optimum jacking pattern is found by minimizing the rate of direction change required for steering and the squares error G of the rate of direction change brought about by possible jacking patterns, as given below:

$$G=\sqrt{\left(K_x\cdot M_x-a_{t+j}\right)^2+\left(K_y\cdot M_y-b_{t+j}\right)^2}\Rightarrow\text{Minimum} \tag{13}$$



(a) N Value and Conversion Coefficient

(b) Overburden Pressure and Conversion Coefficient

(c) Lateral Pressure at Rest and Conversion Coefficient

(d) Modulus of Deformation and Conversion Coefficient

Figure 12 Ground Conditions and Conversion Coefficient

(4) Conversion Coefficient

The rate of direction change measured at 5 cm intervals is infinitesimal, and is thus difficult to detect accurately by gyrocompass. Hence larger directional change was measured, in order to improve the accuracy of the conversion coefficient; the difference between the newest direction and the direction measured 1.0 m earlier will be used as the rate of direction change.

As the conversion coefficient expressed as time series data according to distance excavated results in a huge amount of data, it was decided to organize by frequency the successively calculated conversion coefficients at 0.25 $\times 10^{-3}$ (degree/tonf•m/m) intervals, at the sites where work was carried out, separately for the horizontal and vertical directions. Frequency distributions are usually shown using histograms, but as multiple data cannot be juxtaposed in histograms, the histogram ceiling data were connected using a spline function, as shown in **Figure 11**. The figure also shows horizontal and vertical conversion coefficients, the data quantity, the mean, and the standard deviation.

The conversion coefficient is the ratio between the rate of direction change per 1.0 m excavated and the eccentric moment; its value varies considerably according to the irregularity of the ground and erratic excavation conditions. The actual conversion coefficient distributions obtained were rather erratic, particularly at sites A and B, which have weak ground. However, since the conversion coefficients form a smooth shape at sites C, D, E, and F, it becomes feasible to use the mean values for considering the relationship with the ground conditions. The conversion coefficient in the vertical direction is smaller than in the horizontal direction, except for site C, at which the reverse was true. This is thought to be because the overburden at site C is thinner than elsewhere.

(5) Conversion Coefficients and Ground Conditions

In order to study the relationship between the behavior of a shield affected by eccentric moment and ground conditions, the mean conversion coefficient values (degree/tonf•m/m) and soil constants are shown in **Figure 12.**

a) N Value and Conversion Coefficient

A linear least–squares approximation of the relationship between the mean conversion coefficient value and the N value results in the following equations:

$$\overline{K_x}=(-3.0\cdot N+181)\times 10^{-5}$$

(conversion coefficient r=–0.90)

$$\overline{K_y}=(-2.5\cdot N+141)\times 10^{-5}$$

(conversion coefficient r=–0.98)

where $\overline{K_x}$ ($\overline{K_y}$) is the horizontal (vertical) conversion coefficient.

The relationship between the N value and the conversion coefficients indicates that as the N value becomes larger, the conversion coefficient for both the horizontal and vertical deviations becomes smaller. The correlation coefficient is also high, and correlation is evident. This is thought to be because the smaller the N value, the more easily does the shield machine change direction according to jacking pattern; conversely, the lower N value, the less is the shield machine prone to bending. The conversion coefficient for both the horizontal and vertical directions becomes 0 once the N value reaches values of 50~60, which means that no control can be effected by the jacking pattern.

b) Overburden Pressure and Conversion Coefficient

A linear least–squares approximation of the relationship between the mean conversion coefficient value and the overburden pressure results in the following equations:

$\overline{K_x}=(-0.84 \cdot P_V-116)\times 10^{-5}$
(conversion coefficient r=–0.11)

$\overline{K_y}=(-2.23 \cdot P_V-120)\times 10^{-5}$
(conversion coefficient r=–0.37)

There is no correlation between overburden pressure and the conversion coefficient.

c) Lateral Pressure at Rest and Conversion Coefficient

A linear least–squares approximation of the relationship between mean conversion coefficient value and the soil constant results in the following equations:

$\overline{K_x}=(1.25 \cdot P_0+77)\times 10^{-5}$
(conversion coefficient r=0.13)

$\overline{K_y}=(-1.47 \cdot P_0+95)\times 10^{-5}$
(conversion coefficient r=–0.20)

As with overburden pressure, the lateral pressure at rest does not correlate with the conversion coefficient.

d) Modulus of Deformation and Conversion Coefficient

A linear least–squares approximation of the relationship between mean conversion coefficient value and the logarithm of the modulus of deformation results in the following equations:

$\overline{K_x}=(-62 \cdot \log E_S+254)\times 10^{-5}$
(conversion coefficient r=–0.80)

$\overline{K_y}=(-56 \cdot \log E_S+213)\times 10^{-5}$
(conversion coefficient r=–0.95)

A very strong negative correlation is apparent between modulus of deformation and conversion coefficient, with the conversion coefficient becoming smaller as the modulus of deformation increases. When the horizontal and vertical moduli of deformation reach values of 12,000 and 6,000 respectively, steering can no longer be carried out by means of eccentric moment caused by the jacking pattern.

Through analysis of correlations it was thus found that the soil constants that correlate strongly with the conversion coefficient are the N value and the modulus of deformation. Hence it is clear that the behavior of the shield machine is not determined by the stress in the ground, but by soil constants that express the hardness of the ground, such as the modulus of deformation and the N value.

When the modulus of deformation and the N value become exceptionally large, it will become impossible to steer the shield machine by the eccentric moment effected by the jacking pattern, and a different steering method must be devised.

Note that although several factors, such as excavation conditions (i.e. jacking speed of the shield machine) or the stability of the tunneling face, can affect the steering of the shield machine by its eccentric moment, these were not included in this study.

5. CONCLUSIONS

This study was carried out with the objective of investigating the suitability of a model for steering the shield machine through feedback–prediction control, from the standpoint of soil mechanics. Shield machine behavior results measured during work in different types of ground (at six sites) were used to study the relationship between soil conditions and a) a behavior prediction model and b) regressive parameters.

As a result, the following were found:

1) As the position and attitude of the shield machine could be predicted accurately using past measurements and an autoregressive model, the suitability of the model could be verified.

2) The AR factor, which is a parameter of the behavior prediction model, correlates extremely well with the N value and modulus of deformation of the tunneling face, but does not correlate much with the overburden pressure and lateral pressure at rest.

3) A regressive steering model of when the shield machine is affected by the eccentric moment caused by the jacking pattern showed that, although there is some fluctuation, on average the conversion coefficient is of a suitable value, thus verifying the suitability of the model.

4) The conversion coefficient, which indicates the ratio between the eccentric moment caused by the jacking pattern and the amount of the shield machine's direction change, correlates extremely well with the N value and the modulus of deformation. When the N value and the modulus of deformation of the ground at the tunneling face become extremely large, the shield machine can no longer be steered using the eccentric moment effected by the jacking pattern.

In the study covered by this paper, only the eccentric moment effected by the jacking pattern was considered as a factor affecting direction change in a shield machine. Other than this, the shield machine's size, the excavation conditions, and the stability of the tunneling face would also be factors, but as no qualitative nor quantitative data could be obtained, these were not considered in the study. In future it will be necessary, with the development of more accurate measuring instruments, to pursue this angle based on extensive measurement data.

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