Geotechnical Aspects of Underground Construction in Soft Ground, Mair & Taylor (eds)
© 1996 Balkema, Rotterdam. ISBN 90 5410 856 8

Design and development of underground construction equipment in a centrifuge

S. Imamura, T. Nomoto & K. Mito
Nishimatsu Construction Co., Ltd, Tokyo, Japan

K. Ueno
Department of Civil Engineering, Utsunomiya University, Tochigi, Japan

O. Kusakabe
Tokyo Institute of Technology, Japan (Previously: Department of Civil Engineering, Hiroshima University, Japan)

ABSTRACT: Centrifuge modelling in the field of geotechnical engineering often requires models of construction machines and the simulation of construction processes to clarify the detailed behaviour of construction. Modern advanced mechatronics, including machining and control technologies, are making it possible to fabricate such models. These peripheral technologies, however, are essentially developed in a gravity field environment and are needed to examine in a centrifuge field environment. This paper describes the design method for underground construction equipment with special reference to the problem of earth pressure acting on the lining of a shield tunnel. The paper then verifies the design method for construction equipment in the centrifuge field by means of checking the reproduceability of experiment data and their comparison with data in the field.

1. DESIGN OF MODEL

Figure 1 shows the flow of the design process for a centrifuge model for shield tunnelling with integration of the construction machinery. The key points of this design process are explained below.

(1) Objective and Analysis of Subject Phenomena

The objective of the planned device is measurement of the earth pressure acting on the lining of a shield tunnel. Figure 2 indicates the overlapping relationship between various problems associated with shield tunnelling work. As clearly shown in Fig. 2, earth pressure acting on the tunnel is not the result of simple reciprocal action between the structure and the ground but is a much more complicated issue affected by the construction processes. Because of such complexity, the following modelling details are essential to measure the earth pressure in a centrifuge.

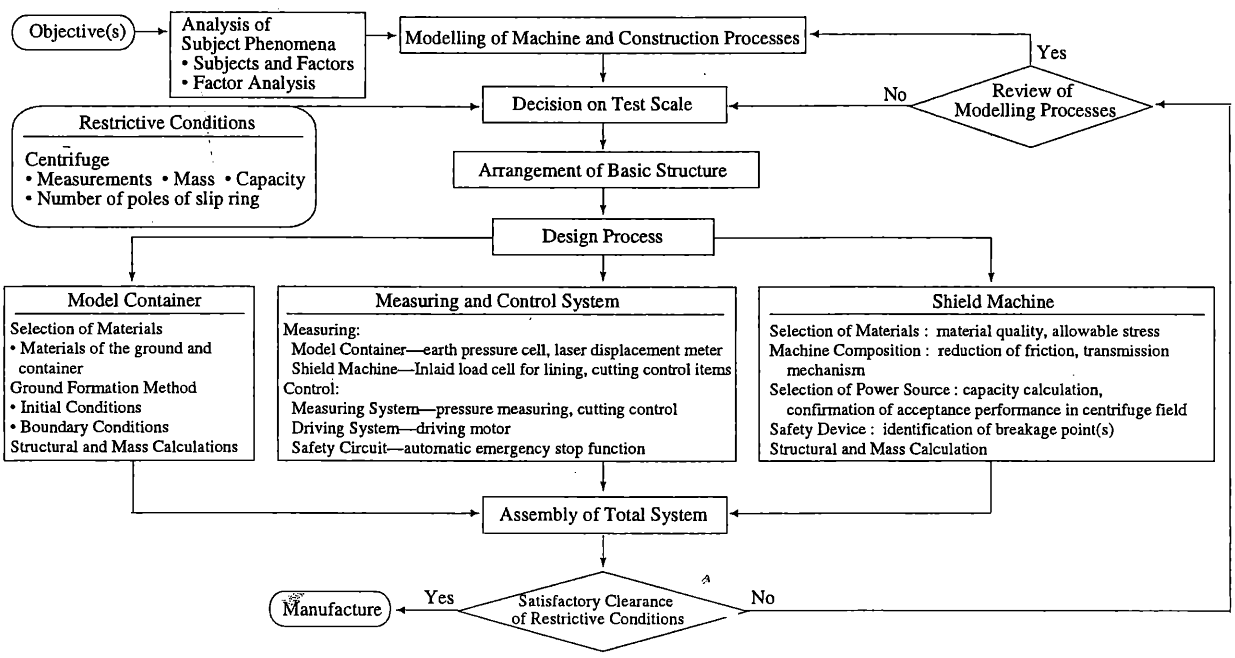

Fig. 1 Design Flow of Model Incorporating Shield Machine

(2) Modelling of Construction Machine and Construction Processes

The present study tries to manufacture a miniature construction machine (shield machine) and construction processes from cutting to tail void formation by means of the modelled driving mechanism of a triple tubes structure (Fig. 3).

These triple tubes represent the shield machine (outer tube), lining/segment (middle tube) and soil discharge mechanism (inner tube). Inlaid load cells and soil discharging screws are installed in the middle tube and the inside of the inner tube respectively.

The cutting process is represented by drilling of the ground by a cutter fixed at the front of the screw conveyer. The thrusting process is represented by the forward movement of the entire triple tubes by the thrust motor while discharging the excavated soil to the back of the screw conveyer. These two processes are called the driving process. The process of tail void formation is simulated by pulling out the outer tube in the opposite direction of the thrusting after the completion of the planned driving process. Consequently, this process of tail void formation is also described as the pulling-out process. In short, at the time of driving, the three tubes remain as a single unit. When the tail void is formed, the outer tube moves backwards while leaving the middle and inner tubes in the ground.

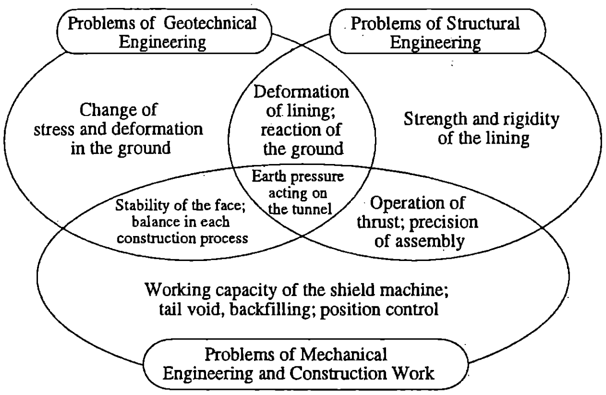

Fig. 2 Problems Associated with Shield Tunnelling Work

(3) Structure

The developed model shield machine was placed on a centrifuge owned by Chuo University (Fujii, N. et. al., 1988) to conduct the test. The structure of the model is largely divided into the container section and shield machine section (Fig. 3). The latter is further divided into the triple tubes section and driving unit section. As the power source for driving, two motors are installed (one for cutting and one for thrusting) at the top and bottom of a supporting frame.

(4) Ground

Assuming simple ground with no special hydraulic conditions, air-dried Toyoura sand is used to create the model ground. The dimensions of the container are 240 mm for the drilling direction, 700 mm for the cross-sectional direction and 700 mm for the vertical direction so that a distance equivalent to 3 D (D = shield diameter) on both sides of the shield machine and a depth of 1.5 D below the shield machine are available to avoid any influence of the boundary conditions on the earth pressure acting on the tunnel. With regard to the initial conditions of the ground, the air pulviation method is used to produce the consistent production in the relative density.

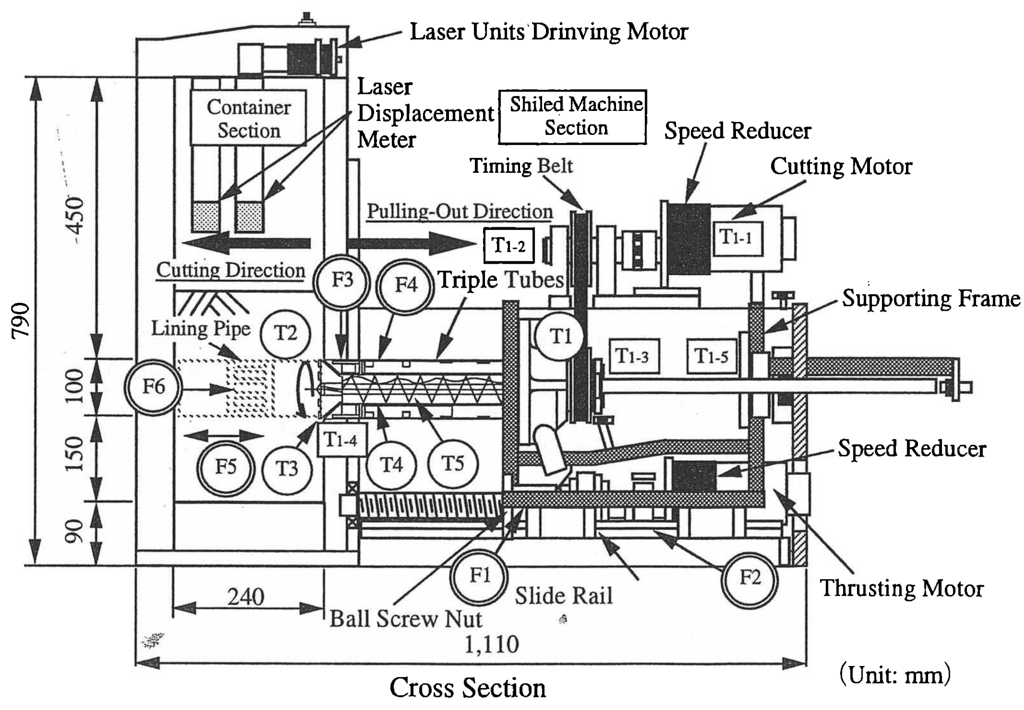

Fig. 3 Thrust and Torque Generating Points of Model Shield Machine

(5) Capacity Calculation for Thrusting Motor

The friction losses for the thrusting motor mainly occur at positions F_1 through F_8 in Fig. 3 and are predicted in the following manner.

a) Mechanical Friction Losses

The friction losses of F_1 through F_4 caused by contact between the mechanical components can be evaluated by the test without soil in the container, i.e. no ground exists inside the container.

① F_1: Friction loss not affected by the acceleration generated at a pre-load nut in the transmission section; empirically predicted to fluctuate between 30% and 100% of the pre-load (1,422.5 N).

② F_2: Friction loss occurring when the main driving unit (mass (m_2) × acceleration (a)) is moving on the slide rail.

③ F_3: Friction loss at the entrance of the container; calculated by multiplying the weight of the triple tubes ($m_3 \times a$) acting on the entrance by some relevant friction coefficient.

④ F_4: Friction loss occurring with the sliding ring positioned between the outer tube and the middle tube when the outer tube is pulled out; calculated by multiplying the weight of the middle and inner tubes acting on the outer tube ($m_4 \times a$) by some relevant friction coefficient.

The predicted values by the test without soil are shown by the lines of prediction (maximum, minimum) in Fig. 4, taking the fluctuation of F_1 into consideration.

b) Friction Losses due to Contact with Ground

The friction losses of F_5 and F_6 caused by contact between the shield machine and the ground occur when the tests with soil in the container, i.e. the model ground exists in the container, are conducted.

① F_5: Friction loss caused by contact between the outer surface of the outer tube and the ground; calculated by multiplying the total earth pressure acting on the outer surface by some relevant friction coefficient and proportional to the outer tube length in the ground and the earth pressure; the earth pressure used for the prediction is the vertical effective earth pressure at the central point of the shield machine under the condition that the earth cover is less than 2 D or at a depth of 2.5 D (constant) under the condition that the earth cover is 2 D or more.

② F_6: Thrust resistance acting on the face; calculated by multiplying the horizontal earth pressure acting on the face by the cross-sectional area; the earth pressure used for the prediction is calculated by multiplying the vertical effective earth pressure at the central point of the shield machine by $K_0 = 1\text{-}\sin \phi$ (coefficient of earth pressure at rest) for the minimum prediction or $K = 1.0$ for the maximum prediction.

Consequently, the predicted value of the test with soil is the sum of F_1 through F_6 and shown by the lines of prediction (maximum, minimum) in Fig. 5.

(6) Capacity Calculation for Cutting Motor

The load for the cutting motor mainly occurs at positions T_1 through T_5 in Fig. 3 and the prediction is conducted in the following manner.

a) Mechanical Torque Loss

The friction loss of T_1 caused by contact between the mechanical components can be evaluated by the test without soil using the model and is the sum of the main torque losses listed below. The basic calculation formula is the weight acting on the bearing multiplied by the friction coefficient multiplied by the radius of the bearing.

① $T_{1\text{-}1}$: Loss at the motor bearing (2 points)

② $T_{1\text{-}2}$: Loss due to the belt tension and weight of the pulley at the two pulleys (2 points)

③ $T_{1\text{-}3}$: Loss due to the belt tension and own weight at the spline support section (one point): because of the negative value of the belt tension, the actual value (absolute value) is the difference between the loss due to belt tension and the loss due to own weight.

④ $T_{1\text{-}4}$: Loss at the cutter support section (one point)

⑤ $T_{1\text{-}5}$: Loss at the tail shaft support section (one point)

Accordingly, the relationship between the level of acceleration and predicted value of the cutter torque in the test without soil is dominated by the level of acceleration and is shown by the line of prediction in Fig. 6.

b) Torque Loss due to Contact with Ground

The torque losses of T_2 through T_6 caused by contact between the shield machine and the ground occur when the tests with soil are conducted.

① T_2: Friction torque loss caused by contact between the cutter face plate and the ground; calculated as T_2 = horizontal earth pressure acting on the face × area of the face plate × 2/3 of cutter radius × friction coefficient; for the present model, it is predicted that this loss takes place at two points, i.e. the frontal section of the face and the inner face of the chamber; the earth pressure used for the prediction is the same as that used for F_6.

② T_3: Friction torque loss caused by contact between the peripheral section of the cutter and the ground; calculated as T_3 = vertical effective earth pressure at the central point of the shield machine × length of the peripheral section × width of the peripheral section × cutter width × friction coefficient; for the prediction using the present model, the width of the peripheral section is considered to be equal to the length between the front of the face and the bottom end of the inner face of the chamber; the earth pressure used for the prediction is the same as that used for F_5.

③ T_4: Friction torque loss caused by transportation of the excavated soil; proportional to the product of the weight of the excavated soil in the conveyor × friction coefficient × screw pitch; the length of the screw conveyer is given as the distance between the blade end of the shield machine and the soil outlet.

④ T_5: Friction torque loss between the surface of the screw blade and excavated soil; the prediction formula is basically the same as that used for F_2.

The predicted value of the test with soil is the sum of T_1 through T_5 and is shown by the lines of prediction (maximum, minimum) in Fig. 7. A comparison between Fig. 6 and Fig. 7 shows that torque loss is largely caused by contact with the ground.

(7) Selection of Motors and Their Performance in Centrifuge Field

The servo motor, which has a wide control range, is selected to function as a thrusting motor and cutting motor. It is confirmed by the energy loss test that the energy loss by the weight of the motor itself in the centrifuge field can be ignored.

(8) Measuring and Control System

Figure 8 shows the measuring and control system used in the test. For the present test, special care is taken not only for the measurement of the earth pressure acting on the tunnel, which is the main objective of the test, but also for the output management of the power source, control of the machine and safety measures to prevent any breakage of the model system. The characteristics of the developed system are listed below.

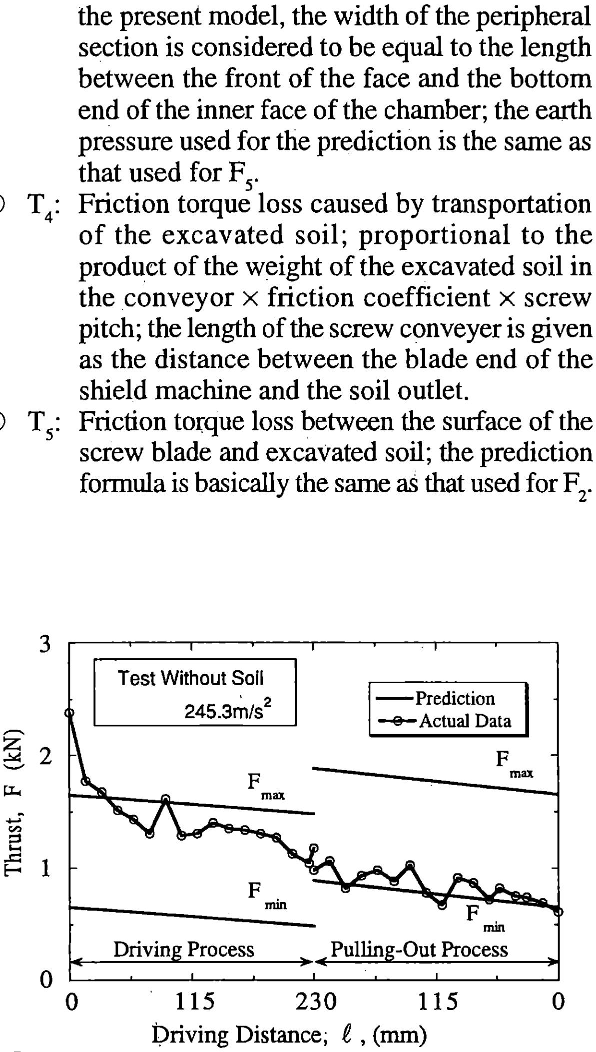

Fig. 4 Load on Thrust Motor in Test Without Soil

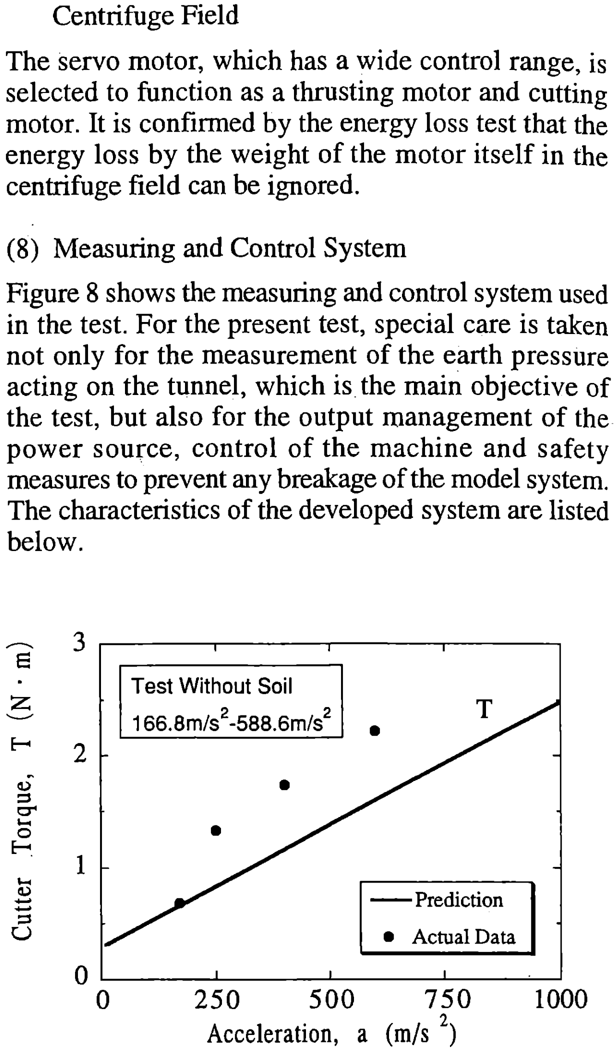

Fig. 6 Load on Cutting Motor in Test Without Soil

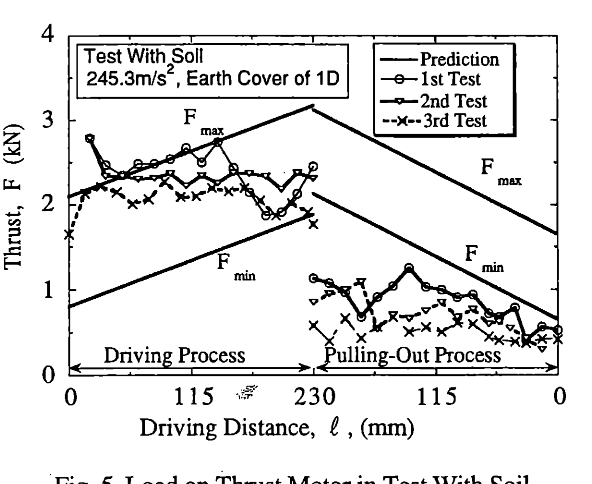

Fig. 5 Load on Thrust Motor in Test With Soil

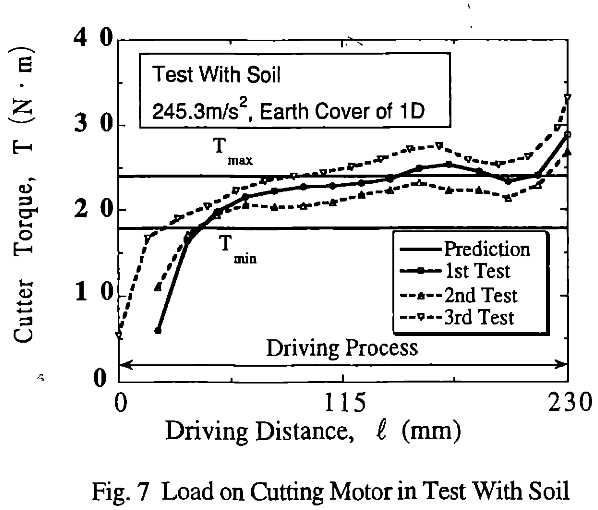

Fig. 7 Load on Cutting Motor in Test With Soil

① With regard to the inlaid load cells (one-way load cells) to measure the earth pressure acting on the tunnel and the buried earth pressure cells, their proper functioning in the ground in the centrifuge field is verified under coordinated conditions of the ground material, relative density and installation depth so that a reliable scope of measurement by these load cells and a calibration line can be established.

② Measurement of the ground surface settlement is conducted by laser displacement meters with high resolution which are made movable by the installation of an exclusive driving motor so that any displacement in the cross-sectional direction of the shield machine can be measured.

③ With regard to the configuration of the measuring system, the installation of a switchbox within the centrifuge field enables omission of the required poles of the slip ring.

④ A sequential control mechanism is adopted for shield machine control, gathering of measurement data and monitoring of the operation to improve the reproduceability of the test and to avoid human error where possible.

⑤ An automatic emergency stop function, relying on such abnormalities of the driving mechanism as abnormal signals indicating overheating of the driving motor and signals indicating excess beyond the control limit, is added to the control circuit.

⑥ An automatic emergency stop function based on the mechanical driving system using signals from the contactless switch is added to the control circuit to prevent destruction by the over-run, etc. of the mechanical driving section.

2. EXAMINATION OF DESIGN METHOD

Based on the results of the shield tunnelling model test, the design method for the construction machine is examined here. The test without soil is conducted with acceleration of 196.2 - 588.6 m/s^2 while the test with soil is conducted with acceleration of 245.3m/s^2 and earth cover of 1 - 4 D.

(1) Thrusting Motor

Figures 4 and 5 show the motor load measurement results of the tests without soil and with soil respectively.

a) Load in Test without Soil

The average thrust generally falls within the range between the maximum and minimum prediction lines. In the prediction, the load in the pulling-out process is put higher than that in the thrusting process. The actual data show the opposite.

b) Load in Test with Soil

In the thrusting process, the observed thrust generally falls within the predicted range. However, the observed thrust in the pulling-out process is much lower than the predicted value and is similar to that in the test without soil. This result suggests that the loss F_5 caused by contact between the outer face of the outer tube and the ground is much lower than predicted and that the thrusting resistance F_6 at the front of the face is dominant.

(2) Cutting Motor

Figures 6 and 7 show the motor load measurement results of the tests without soil and with soil respectively.

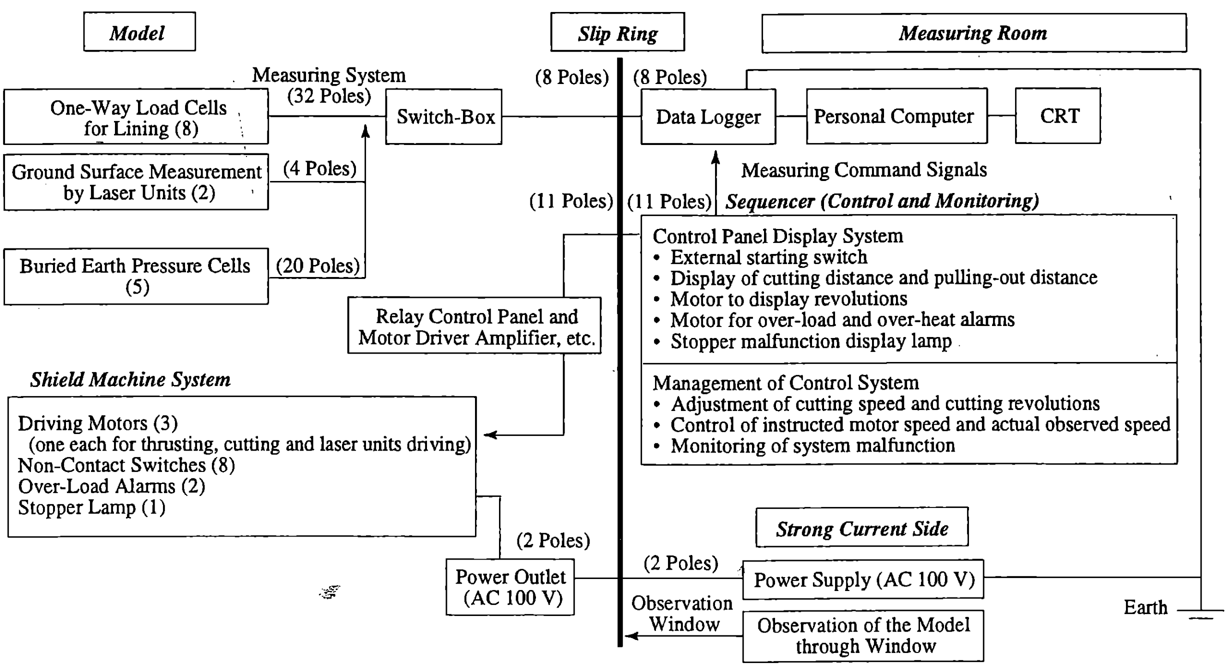

Fig. 8 Planning Drawing for Measuring and Control System

a) Load in Test without Soil

The average torque is slightly higher than the line of prediction but well catches the movement of load in response to the increased acceleration, suggesting that the prediction is fairly reasonable.

b) Load in Test with Soil

The observed data generally fall in the predicted range for a driving distance of 50 - 200 mm but are lower than the prediction for a distance of 0 - 50 mm and are higher for a distance of 200- 230 mm. The reason for the lower than predicted data for the distance of 0 - 50 mm is that the excavated soil does not yet fill the entire length of the conveyer, resulting in small F_4 and F_5 losses. When the shield machine approaches the wall of the container, the earth pressure between the shield machine and container wall changes to the passive side to increase the value of T_2 at the face plate.

Given the above results, it can be judged that the formulae created to predict the thrust and cutting motor loads are generally appropriate.

(3) Reproduceability of the Test

Figures 9 and 10 show the measurement results of the earth pressure acting on the tunnel and the surface ground displacement in the cross-sectional direction respectively. Three sets of the measurement values are almost identical, indicating the reasonable reproduceability of the test, in turn proving the success of automatic operation under sequential control.

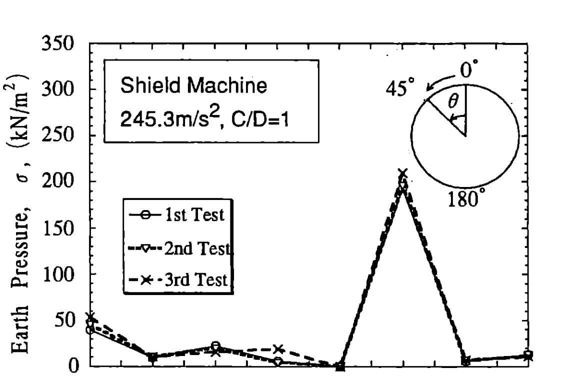

Fig. 9 Measurement Results of Earth Pressure Acting on Tunnel

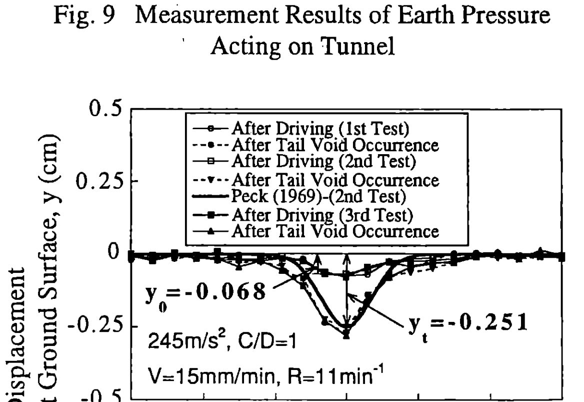

Fig. 10 Ground Surface Displacement Measurement Results for Cross-Sectional Direction

(4) Comparison with Empirical Data

Figure 10 compares the settlement at the central section after formation of the tail void with the normal probability curve (Peck, 1969). The three sets of measurement data agree with the said settlement curve, indicating the appropriateness of the modelled construction process to simulate ground surface displacement.

3. CONCLUSIONS

The test results prove that the design method used for the shield machine in a centrifuge is appropriate. The knowledge gained by this study is outlined as follows.

① It is of essence to make extensive use of advanced mechatronics and control technologies in a test using a model integrated with a construction machine to ensure reproduceability of the test and to represent the complexity of the construction processes.

② While it is possible to use empirical formulae established in the gravity field as formulae to calculate the required capacity of power sources, it is of essence to give sufficient allowance for the loss due to contact with the ground. It is also necessary to create a measuring system capable of comparing the theoretical values with the calculated values from load data on the power sources.

③ It is necessary to prove the appropriateness of the modelling of construction processes by means of comparing test data with empirical data obtained from past construction work.

④ The test results suggest that the testing method involving a construction machine in the centrifuge field is an effective means of developing a new construction method as well as new construction machinery.

REFERENCES

Nomoto, T., Mito, K., Imamura, S., Ueno, K. and Kusakabe, O. (1994): Miniature shield tunnelling machine in a centrifuge, Centrifuge '94, pp. 699 - 704.

Fujii, N., Kusakabe, O., Keto, H., Maeda, Y. (1988): Bearing capacity of a footing with an uneven base on slope: Direct comparison of prototype and centrifuge model behavior, Centrifuge '88, pp. 301 - 306.

Peck, R. B. (1969): Deep excavation and tunnelling in soft ground, Proceedings of the 7th ICSMFE (Mexico), State of the Art Volume, pp. 225 - 290.