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Centrifuge modelling of construction processes of shield tunnel

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ABSTRACT: The earth pressure acting on the lining of a shield tunnel is a matter of interaction between the lining and the ground and is greatly influenced by the construction processes. The earth pressure acting on the tunnel changes from an active to a passive state depending on the earth pressure and water pressure acting on the face, face retaining pressure, amount of excavated and waste soil, amount of tail void, amount of grouting and relative relationship between the grouting pressure and surrounding earth pressure. The earth pressure is also largely influenced by the stiffness of the lining.

The lining design is conducted by a calculation method using the earth pressure acting on the tunnel established by experience. As the earth pressure acting on the tunnel in the field changes with the construction processes as described above, it is necessary to examine the earth pressure by means of physical modelling and field measurements to confirm the validity of the design.

The physical modelling of the earth pressure acting on the tunnel has so far been limited to the earth pressure on underground buried pipes. For this reason, it is necessary to establish a reliable earth pressure acting on the tunnel by means of physical modelling to simulate the initial ground stresses and shield construction processes. The present study aims at solving the above-mentioned problem. It tries to clarify the effects of construction processes on the earth pressure acting on the tunnel by means of earth pressure measurements using a miniature shield tunneling machine for a centrifuge that can simulate the construction processes from cutting to tail void formation.

1. SHIELD TUNNEL PROCESSES AND THEIR MODELLING

Figure 1 shows a conceptual illustration of the stress changes in the ground around a tunnel during the shield tunnelling processes in sandy soil ground, showing that the earth pressure acting on the tunnel is affected by all construction processes. Consequently, the following issues are important when attempting to evaluate the earth pressure acting on the tunnel using a centrifuge model.

① Reproduction of the initial stress conditions in the ground.
② Simulation of the construction processes, from cutting to stabilisation of the lining.
③ Reproduction of a scale similar to the reality in terms of the tail void thickness, etc.
④ Reproduction of a stress level similar to the reality in terms of the lining weight, etc.
⑤ Reproduction of the geometrical conditions and external force conditions for the outer surface of the tunnel.

Based on the knowledge acquired by previous studies and the concept of the tail void formation process shown in Fig. 2, the following modelling of the shield tunnelling processes is conducted (Nomoto, T. et. al., 1994).

① The initial stress conditions in the ground are reproduced by creating ground under the situation of no lining being placed in the container.
② The cutting and thrusting processes (driving process) are simulated by means of actually making the shield model operate in the centrifuge acceleration field and cut through the ground with correctly modelled initial stress conditions in the container.
③ The tail void formation process (pulling-out process) is simulated by pulling-out the external tube (shield tube) in the opposite direction of the thrusting after completion of the driving process.
④ The lining section is simulated by the middle tube (lining tube) located inside the shield tube which has one-way load cells to measure the earth pressure (inlaid earth pressure cells).
⑤ The backfilling process is omitted as a pending issue because it is necessary to solve the question of the time similarity of the model in relation to the solidifying time of the filling material, etc.

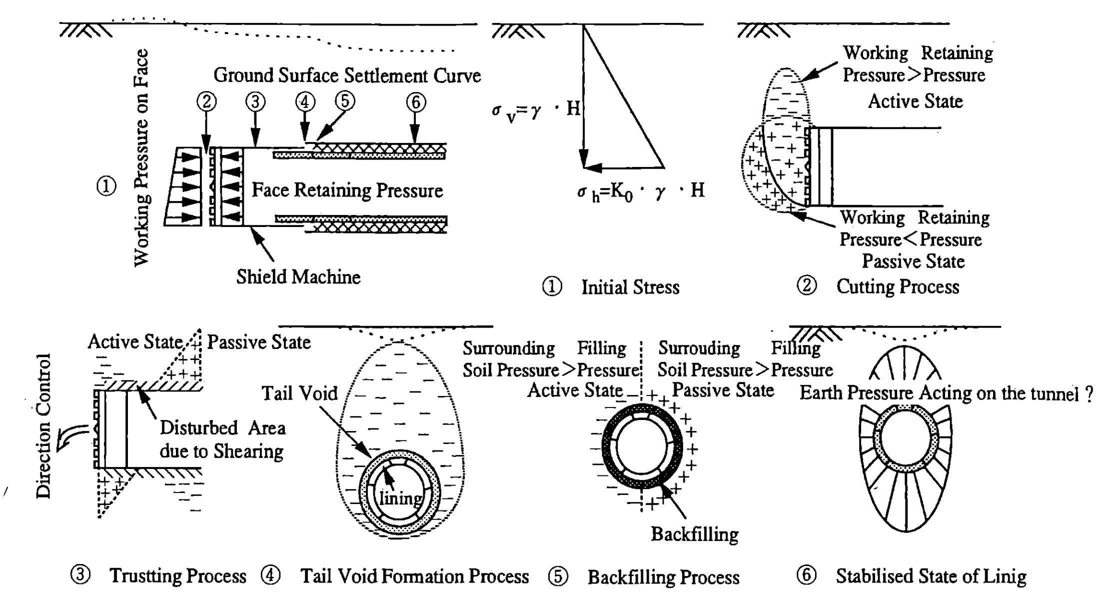

Fig. 1 Conceptual Illustration of Stress Changes in Shield Tunnel and Ground

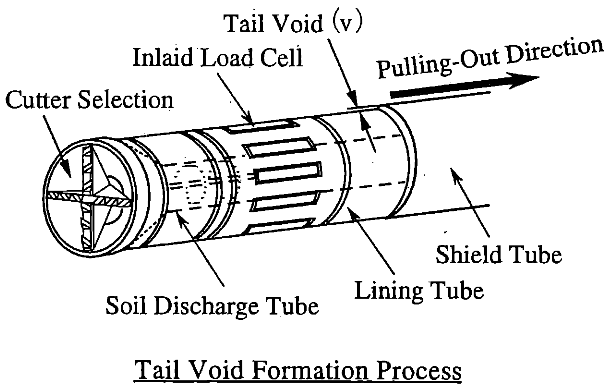

Fig. 2 Simulation Method in Shield Test

2. SHIELD TUNNELLING MODEL

Figure 3 shows a miniature shield tunneling machine for a centrifuge.

(1) Structure

The structure of the shield tunnelling model is largely divided into the container section and shield machine section which is further divided into the triple tubes section, which models the shield tunnel structure, and the driving unit section.

The container is made of duralumin to give a light weight structure. The longitudinal measurement, i.e. thrusting direction of the shield machine, of the container is 240 mm in the case of the present model as there is a limit on the total length of the container, triple tubes and driving unit, etc. The design structural strength is capable of withstanding 100 G (G = gravitational acceleration) with an earth cover thickness of 4 D (D = external diameter of the shield machine).

The shield tube is made of stainless steel and has a diameter of 100 mm and a thickness of 2 mm. The lining tube has a diameter of 96 mm as shown in Fig. 4 and the tail void (v) on one side is 2 mm. Eight earth pressure cells are inlaid in the lining tube. The weight of this 150 mm long tube, modelling the actual lining, is 17.2 N, giving an overall density of 15.9 kN/m^3, which is almost equal to the weight of the soil to be excavated (density 15.3 kN/m^3).

The power is provided by the cutting motor and thrusting motor. The former is located on the upper side of the triple tubes supporting frame parallel to the tunnel axis while the latter is located at the lower side of the same supporting frame parallel to the tunnel axis.

(2) Measuring

Figure 5 shows the measuring and control system used in the shield test. The measuring items in the test are the earth pressure acting on the tunnel, ground surface displacement, underground earth pressure and cutting control. The measuring instruments are controlled by a sequencer, as in the case of the operation of the shield model, and the measurement data are designed to be recorded by the data logger.

With regard to the earth pressure acting on the tunnel, the earth pressure acting on a relatively rigid lining is assumed and the measuring is conducted in the normal direction.

The inlaid load cells have a pressure detecting face of 10 mm by 42 mm with a measurable pressure range of up to 490 kN/m^2. The face has a curvature matching that of the lining and silicon rubber is filled into the circumferential gaps to prevent the inflow of sand particles. The system is designed to permit

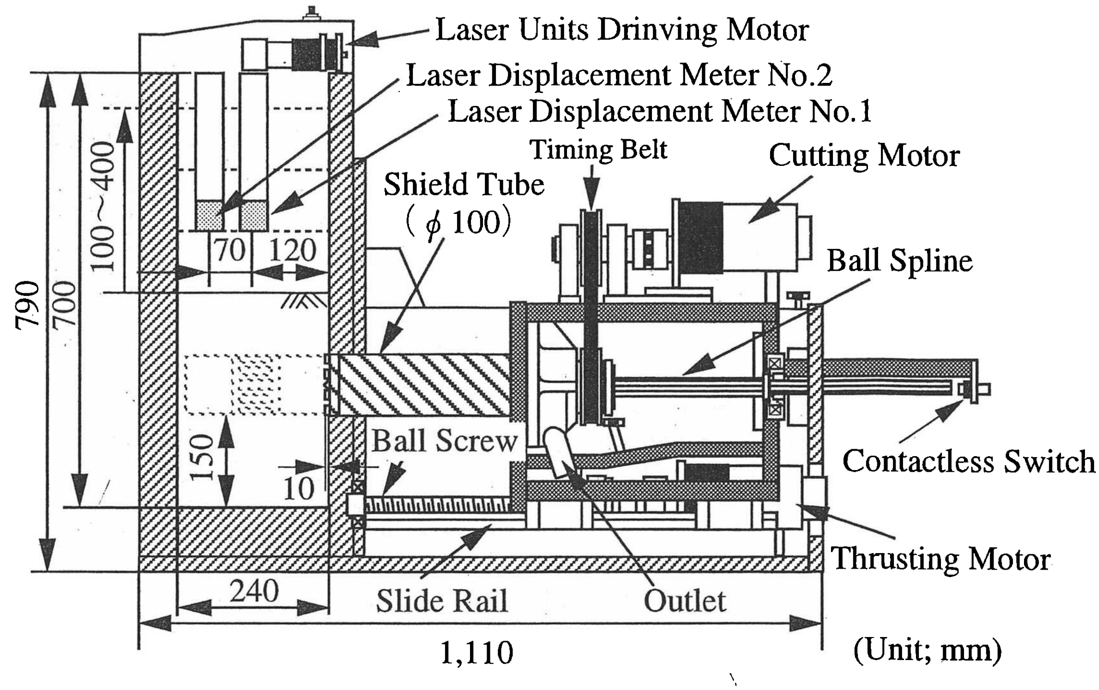

Fig. 3 Conceptual Drawing of Shield Model

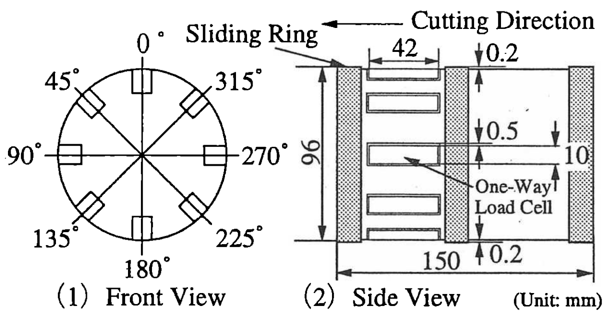

Fig. 4 Lining Tube

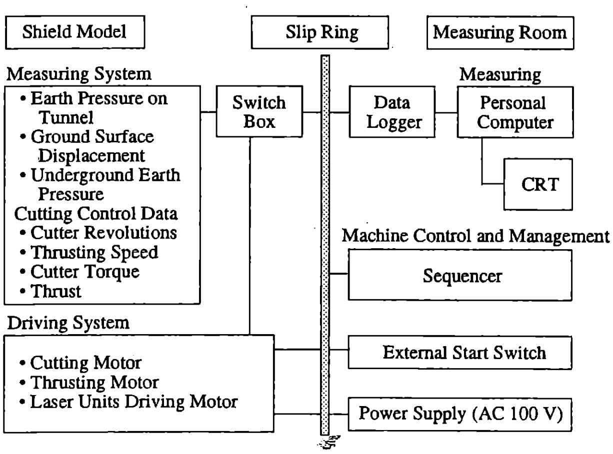

Fig. 5 Planning Drawing of Measuring System (Imamura, S. et. al., 1996)

measurement at any time interval from commencement of the operation of the shield model to the end of the test.

In the case of ground surface displacement measurement, two laser displacement meters are used. These displacement meters are moved by the motor on the guide rail located in the upper section of the container in the cross-sectional direction vis-a-vis the tunnel. The actual measuring is conducted in the specified centrifuge field by means of measuring the shift of the two cross-sections of the tunnel before and after the test and also the shift of two fixed points on the tunnel axis.

The purpose of measuring the underground earth pressure is to establish the changes of the underground earth pressure during shield tunnelling work, i.e. impacts of the shield thrust and changes of the underground earth pressure at the time of tail void formation. Three types of earth pressure cells to measure the underground earth pressure (earth pressure cells embeded in the ground) are used with respective ranges of 0.98, 1.96 and 2.94 MN/m^2 (diameter: 30 mm for all).

The purpose of measuring the cutting control data is to ensure the normal operation of the shield model and the measuring subjects are the cutter revolutions, thrusting speed, cutter torque and thrust, etc. Based on these data, it is possible to establish the relationship between the cutting conditions and capability of the system and, therefore, to predict the limits of the centrifuge field in which the test in question is conducted.

3. TEST USING CENTRIFUGAL MODEL

(1) Test Conditions

The developed test device is capable of conducting the following three types of tests.

① Buried Tube Test
The lining tube is directly buried in the container and the earth pressure acting on the lining tube is measured in the specified centrifuge field, created by an increase of the centrifugal acceleration.

② Tail Void Test
The shield model is buried in the container and only the shield tube is pulled out in the specified centrifuge field to create a tail void (tail void ratio: 2 v/D = 4.0%) so that the earth pressure acting on the lining tube left in the ground can be measured.

③ Shield Test
The shield model is thrust through the entrance of the container and, after thrusting for 230 mm, the shield tube is pulled out to create a tail void for measurement of the earth pressure acting on the lining tube.

The test conditions are a centrifugal acceleration of 25 G (245 m/s^2), an earth cover of 1 - 4 D, a thrusting and pulling-out speed of 15 mm/min and a cutting revolution of 11 rpm. The prototype is equivalent to a 2.5 m diameter shield machine. To create the model ground, air-dried Toyoura sand is used for all the tests and the air puluviate method is used to create an approximate density (Dr) of 70% (ϕ max = 42°).

(2) Earth Pressure Acting on the Tunnel

Figure 6 shows the inlaid load cell measurement results under the test condition of earth cover of 1 D.

The buried tube test results show a generally symmetrical distribution of the measured data and stress concentration at the top of the tube (0°) and bottom of the tube (180°). The earth pressure at the top of the tube is much larger than the entire earth cover pressure(Fig.7).

The tail void test results also show a generally symmetrical distribution of the measured data. Unlike the buried test results, however, the stress concentration is found at the 135° and 225° positions at the underside of the tube. This is presumably due to the fact that the faster displacement speed of the sand than the pulling-out speed makes the sand support the lining tube in areas near 135° and 225°.

The shield test results do not show a symmetrical pattern and indicate a noticeable stress concentration at 225°. This is presumably caused by the formation of a passive soil pressure area in the direction of 225° as the interaction between the cutting and soil discharge mechanism affects the soil pressure around the shield.

These test results clearly show that the distribution pattern of the earth pressure acting on the tunnel is largely determined by differences in the construction processes. Figure 7 shows the relationship between the cover-to-diameter ratio (C/D: C = earth cover, D = shield diameter) and the earth pressure acting on the top side of the tunnel.

The earth pressure acting on the tunnel is much smaller than the entire earth cover pressure and shows the character of loosening earth pressure. Compared to the loosening earth pressure by Terzaghi's method(Terzaghi, 1959), the earth pressure acting on the tunnel shows good conformity with the method

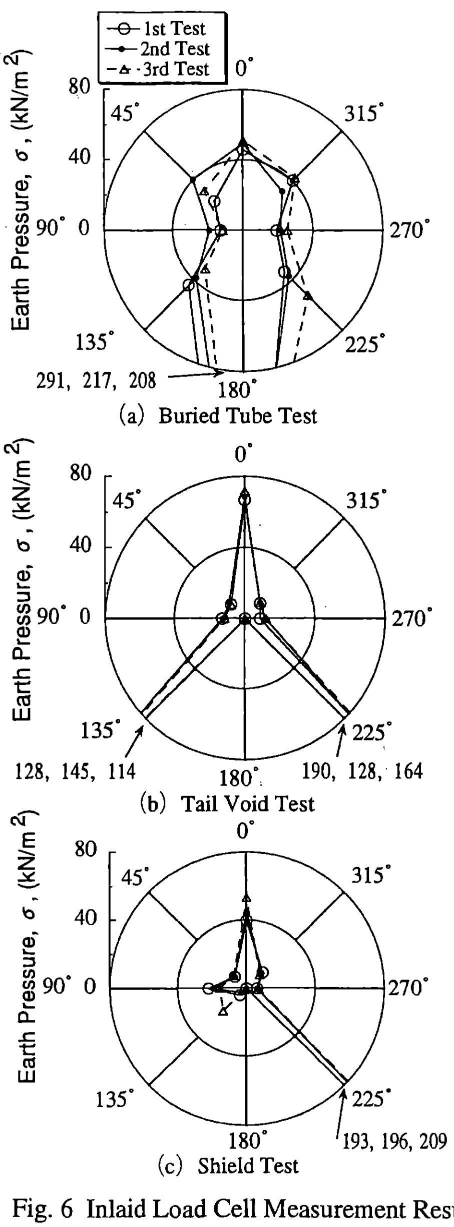

Fig. 6 Inlaid Load Cell Measurement Results (245 m/s^2, C/D of 1)

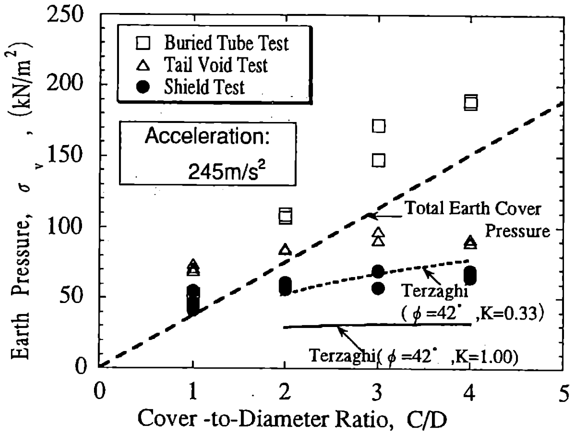

Fig. 7 Relationship Between Earth Cover Pressure and Earth Pressure Acting on the Top Side of the Tunnel

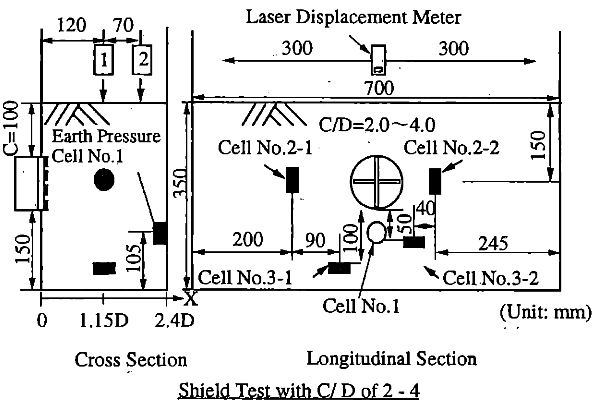

Fig. 8 Measuring Locations of Earth Pressure Cells Embeded in the Ground

under the conditions of $\phi' = 42°$ and K = 0.33. As the observed value is approximately double the value under the condition of K = 1.0, which is used in the current design practice, it is necessary to properly confirm the differences through a further series of tests involving different conditions.

(3) Underground Earth Pressure

Figure 8 shows the measuring locations of earth pressure cells embeded in the ground. Figure 9 shows the observation data on the underground earth pressure in the shield test (third test; 245 m/s², C/D = 4, Cell No.1, Cell No.2-2, Cell No.3-2). In Fig. 9, K and Kp show the stress ratio values (σ_h/σ_v) and passive earth pressure coefficient ($\phi' = 42°$).

The reading of earth pressure cell No. 1 (to measure the horizontal earth pressure at the lower section of the shield front) starts to increase as soon as the cutting operation commences, reaching the maximum level when the cutter is away from the cell at 0.5 D. During the tail void formation process, the value instantly drops and stays unchanged thereafter.

The reading of earth pressure cell No. 2-2 (to measure the horizontal earth pressure at the side of the shield at 0.5 D) starts to increase as soon as the cutting operation commences, reaching the maximum level when the cutter is passing the measuring point, followed by a gradual decline. During the tail void formation process, the earth pressure suddenly drops and then stabilises at a lower earth pressure level than the initial level. The readings of cell No. 3-2 (to measure the vertical earth pressure at the lower section

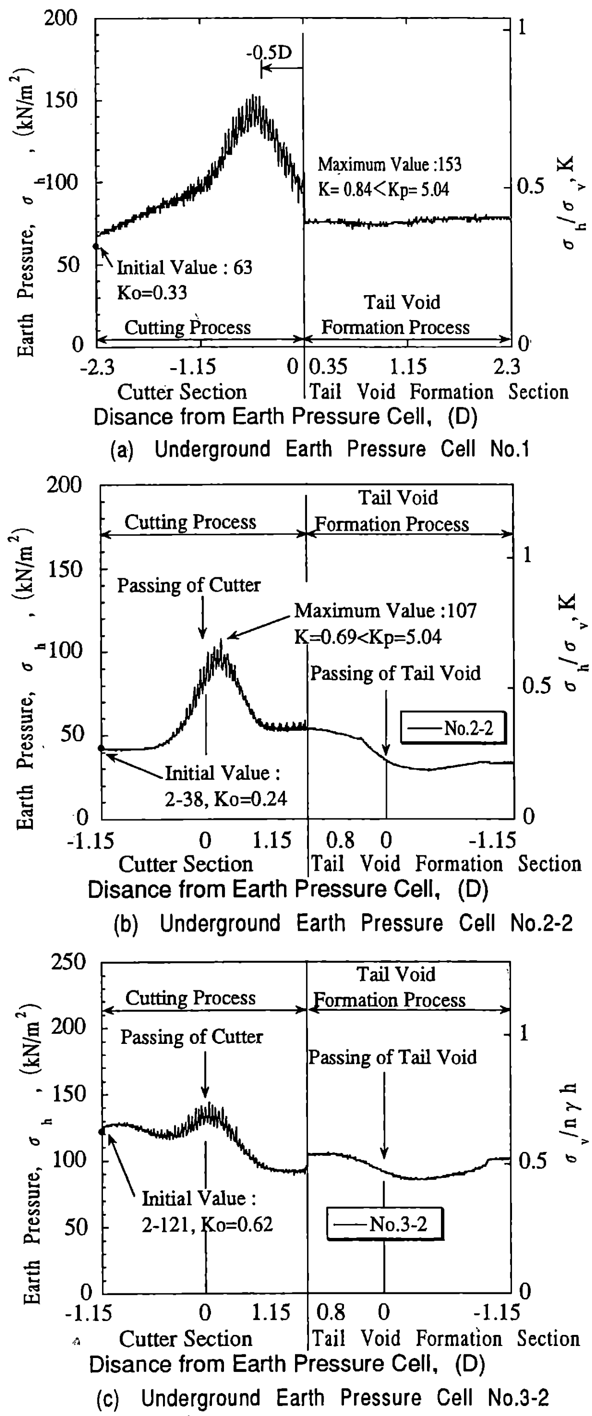

Fig. 9 Underground Earth Pressure Cell Measurement Results (245 m/s²; C/D = 4; 3rd Test)

of the shield at 0.5 D) show similar fluctuations to those of cell No. 2-2 although the level of the absolute values is lower.

Despite control to minimise excess excavation by the cutting operation in the shield test, it is observed that the surrounding earth pressure increased and approached towards the passive side during the cutting process. This suggests that the balance between the volume of excavated soil and the volume of earth discharge is maintained by making the surrounding earth pressure passive as the cutting and soil discharge mechanism of the model, composed of a cutter and screw, basically relies on stabilisation of the sand to maintain stability of the face.

(4) Ground Surface Displacement

Figures 10 (a) - (c) show the measurement results for ground surface displacement at the central point of the container in the cross-sectional direction in the tail void test (C/D = 1) and shield test (C/D = 1 and 4). In Fig. 10 (b), normal probability curve (Peck, 1969) is projected to compare the settlement recorded at the central part of the shield. The measurement data generally conform to normal probability curve by Peck, indicating the appropriateness of the method used by the model to represent the shield tunnelling processes.

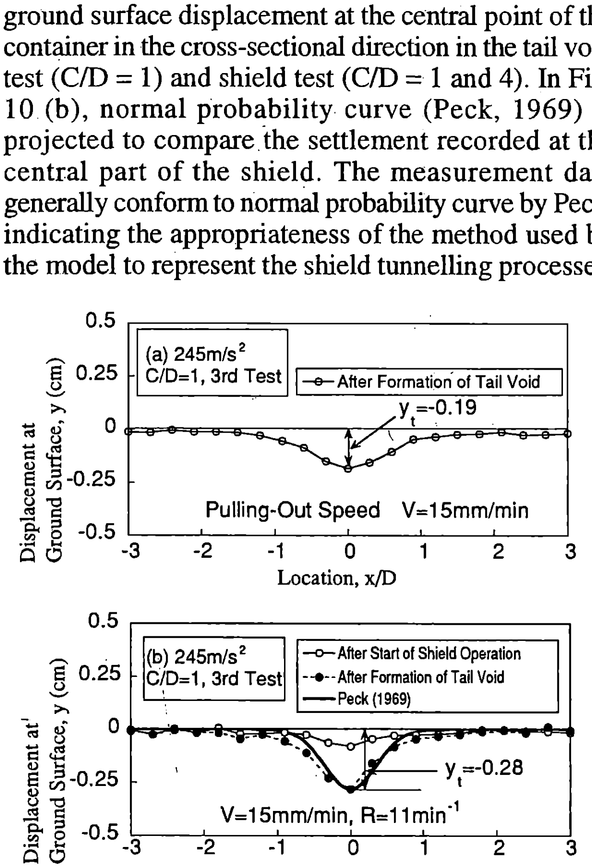

Fig. 10 Ground Surface Displacement Measurement Results

Comparison between Fig. 10 (a) and Fig. 10 (b) shows a slightly smaller volume of settlement and a gentler settlement pattern in the tail void test. In the shield test, slight settlement of the ground surface is observed during the driving process. In Fig. 10 (c), the volume of settlement and settlement pattern at the end of each process are smaller than those seen in Fig. 10 (b), implying the occurrence of loosening earth pressure(also see Fig.7).

4. CONCLUSIONS

The knowledge gained by this study is outlined as follows.

① The distribution pattern of the earth pressure acting on the tunnel in the three tests slightly differs, indicating the necessity to clearly represent the type of construction process involved in a test designed to determine the earth pressure acting on the tunnel. The cutting method requires improvement.

② When the earth cover thickness is 2 D or more, the earth pressure acting on the top side of the tunnel becomes loosening earth pressure, the behaviour of which is similar to that of the earth pressure obtained from Terzaghi's formula (K = 0.33). The level of loosening earth pressure significantly varies depending on the value of K, necessitating further study in this regard.

③ In regard to underground earth pressure measurement, an increase of the earth pressure and residual stress, etc. are recorded, reconfirming the necessity to reproduce the construction process in the shield test and to clarify the relationship between the ground stress and earth pressure acting on the tunnel.

④ The measurement results on the ground surface displacement conform to empirical knowledge, indicating the appropriateness of the representation of construction processes by the developed model.

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