*Geotechnical Aspects of Underground Construction in Soft Ground, Kusakabe, Fujita & Miyazaki (eds)*
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# Displacement of saturated sand during slurry shield driving

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ABSTRACT: The aim of this study is to develop a laboratory ground movement measuring device and apply it to a model test of shield tunneling. The thin flexible metal plate was used for measuring ground displacement, to which the strain gauges were affixed. The calibrations of soil displacement obtained from this measuring device were carried out by the trap door tests. The potential of the laboratory ground movement measuring device was demonstrated for the use to measure the ground displacement during shield driving. Furthermore, a series of model tests were carried out to investigate the ground displacement behaviour during shield machine driving.

## 1 INTRODUCTION

It is not possible to avoid ground displacement during slurry shield driving. Therefore, many model tests using miniature shield machines have been conducted to investigate the mechanism of ground displacement (Nomoto et al. 1997). However, it is difficult to measure the small magnitude of ground displacement existing in the soil container.

The aim of this study is to develop a laboratory ground movement measuring device and apply it to model tests of shield tunneling. A thin flexible metal plate to which the strain gauges were attached was used for measuring ground displacement. The flexible metal plate was embedded within the ground. The deflection of the metal plate was obtained from the measured output from the strain gauge, using the finite difference solution of the differential equation of a beam.

Firstly, the calibrations of soil displacement obtained from this measuring device were carried out. The flexible metal plate was embedded within a sand container having a trap door at its bottom. The strain gauges values as well as directly observed displacement values of the device were recorded in accordance with the movement of trap door.The potential of the laboratory ground movement measuring device was thus demonstrated for use in measuring ground displacements during shield machine driving.

Secondly, the large soil container was prepared to investigate the ground displacement behaviour during shield machine advancement in the laboratory. The miniature slurry shield machine was driven in saturated sand. A series of model tests were carried out to investigate the influence of the magnitude of slurry pressure on the ground displacement during shield machine driving. The soil displacement, earth pressure and pushing pressure on the cutting face were measured while using a range of face slurry support pressures. The amount of excavated soil during machine driving was also measured.

## 2 CALIBRATION TESTS

### 2.1 *Setup of a laboratory ground movement measuring device*

The laboratory ground movement measuring device which was developed in this study is shown in Figure 1. This device is similar to the sensor developed by Shimazu et al. (1983). The thin flexible metal plate of 1 mm thickness to which strain gauges were affixed was used for the measuring ground displacement. The device was covered by a water resistant tube in consideration of the use under water table. The plates were made of a copper beryllium alloy, whose elastic coefficient was about 127 GN/m$^2$. The length of strain gauge was 5 mm and the gauge resistance was 120 Ω. The Wheatstone bridge circuit was a double active half bridge, since the strain gauges were attached to both sides of the metal plate. The ground displacement was obtained from the measured output form the strain gauges, using the finite difference solutions of the differential equation of beams.

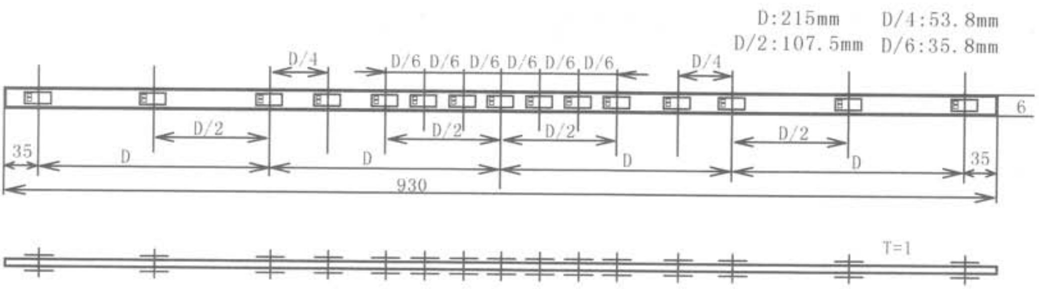


Figure 1. Laboratory ground movement measuring device.

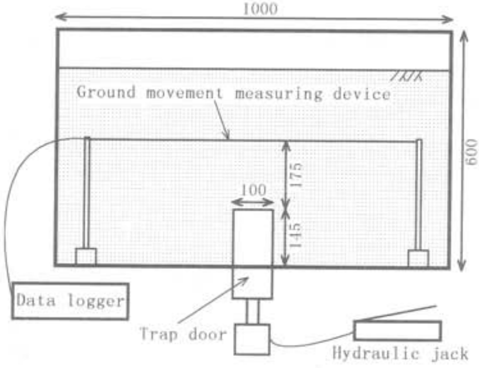


Figure 2. Sand container for calibration tests (in mm).

## 2.2 *Method of calibrations and equipment*

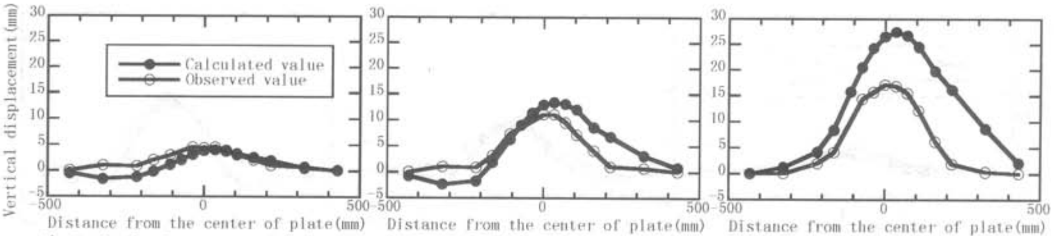
A schematic view of the sand container used for the calibration tests can be seen in Figure 2. The flexible metal plate was embedded within the sand container, whose dimension was 1000 × 600 × 100 mm. The trap door of 100 mm width was installed at the bottom of the sand container, and could be displaced upward and downward by the hydraulic jack. If the hydraulic jack moved upward, the sand was pushed up passively. If the hydraulic jack moved downward, the sand was displaced downward actively. The front side of sand container was made of transparent glass to observe the sand displacement directly during the trap door movement. Dry silica sand #6 ( $\rho_s = 2.56$ g/cm$^3$, $D_{50} = 0.23$ mm) was used and compacted to the dry density of 1.47 (g/cm$^3$) in the tests. The strain gauges values as well as directly observed displacement values of the device through the transparent glass were recorded in accordance with the movement of trap door. The displacement of the device was measured using markers placed on the surfaces of the strain gauges.

## 2.3 *Results of calibrations*

Figure 3 presents the results of calibration in the passive movement, The flexible metal plate was embedded initially in the horizontal position. As the jack displacement increased, the difference between calculated and observed values increased. Figure 4 presents the results of calibration in the active movement. When the hydraulic jack moved downward up to 10 mm, the sand displacement obtained from measured strain values is almost the same as the directly observed value. However, as the jack displacement becomes greater than 10 mm, the accuracy of this measuring device reduced significantly in the central part of the metal plate. The above results show that this device is capable of measuring small magnitude of ground displacements.

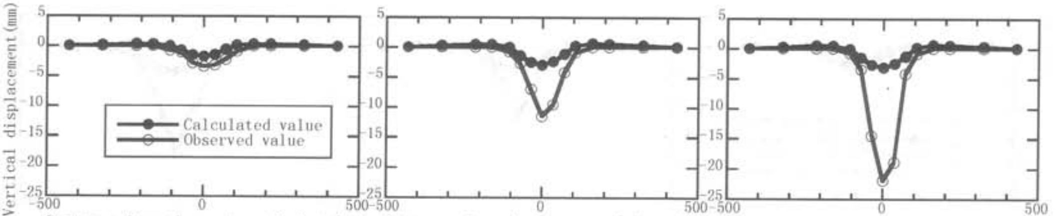
The reason why the sand displacement obtained from measured strain value was very different from the directly observed values, particularly for the active movement, can be explained as follows. The sand displacement in the active movement became exceedingly local in comparison with that of the passive movement. As the sand displacement increased, the deflection of metal plate became large in the passive movement. However, in the active movement, as the sand displacement increased, the flexible metal plate can not follow precisely the sand displacement, which leads to the discrepancy between calculated and observed values. It can be thus concluded that the accuracy of the laboratory ground movement measuring device reduces in the case that the ground displacement becomes exceedingly local.

The flexible metal plate with strain gauges had inevitable errors mainly due to the confinement of water resistant tubing, which protected the strain gauges from water when used within saturated soil. The maximum magnitude of error was measured to be around $\pm 300\,\mu$ using the known radius of curvature. Therefore, the measured values of strain gauges up to $\pm 300\,\mu$ were not able to be used to obtain the sand displacement. To gain the measured strain gauge values greater than $\pm 300\,\mu$ , the



1) Jack displacement 10(mm) 2) Jack displacement 20(mm) 3) Jack displacement 30(mm)

Figure 3. Results of calibration when the plate was embedded initially in the horizontal position (passive movement).



1) Jack displacement 10(mm) 2) Jack displacement 20(mm) 3) Jack displacement 30(mm)

Figure 4. Results of calibration when the plate was embedded initially in the horizontal position (active movement).

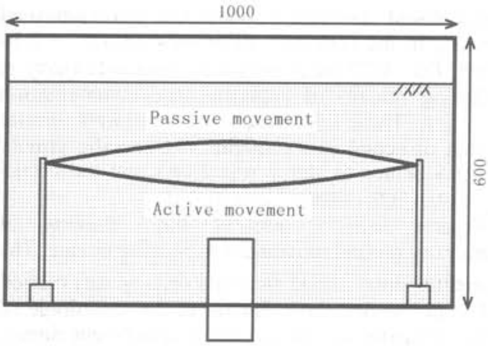


Figure 5. Rounded shapes of embedded metal plate.

flexible metal plate with strain gauges was embedded initially in the rounded shape(see Figure 5). If tested passively, the shape of the embedded plate was concave downward. If tested actively, the shape was concave upward. Calibration tests were also conducted using an initially rounded shape.

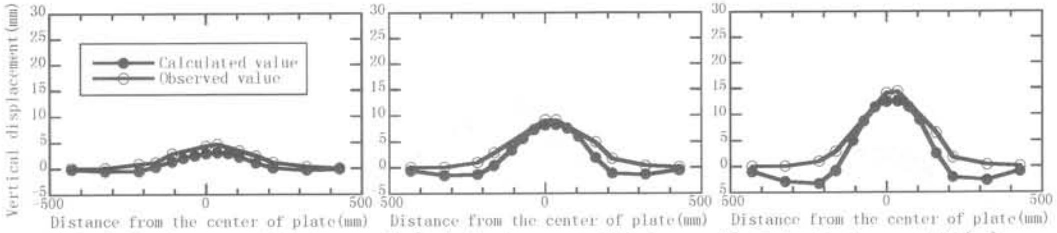
Figure 6 presents the results of calibration in the passive movement. At this time the flexible metal plate with strain gauges was embedded initially in the rounded shape. As can be seen in the figure, the sand displacement obtained from measured strain values is almost the same as the directly observed value. The results of calibration in the active movement are presented in Figure 7. As can be seen in the figure, when the hydraulic jack moved downward up to 10 mm, the sand displacement obtained from measured strain values is coincident with the directly observed value. However, when the hydraulic jack movement becomes greater than 10 mm, the accuracy of this measuring device declines sufficiently.

It can be thus concluded that these initial deformations of the metal plate has greatly improved the correspondence between the calculated values and observed ones. The laboratory ground movement measuring device developed in this study is available for measuring ground displacement during shield machine driving, unless the ground displacement is exceedingly local.

## 3 MODEL TESTS FOR SHIELD TUNNELLING

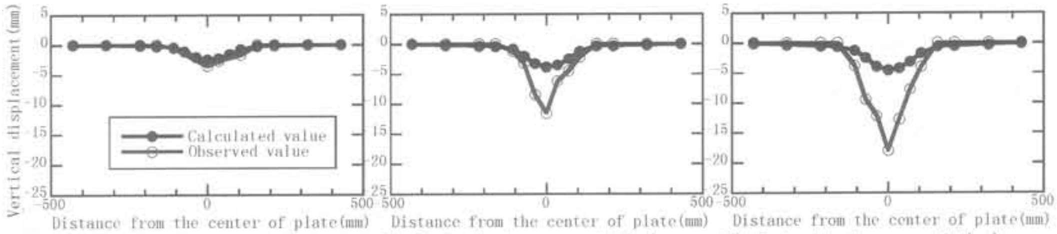
### 3.1 *Method of model tests and equipment*

The large soil container was prepared to investigate ground displacement behaviour during shield machine advancement in the laboratory. The



1) Jack displacement 10(mm) 2) Jack displacement 20(mm) 3) Jack displacement 30(mm)

Figure 6. Results of calibration when the plate was embedded initially into a rounded shape (passive movement).



1) Jack displacement 10(mm) 2) Jack displacement 20(mm) 3) Jack displacement 30(mm)

Figure 7. Results of calibration when the plate was embedded initially into a rounded shape (active movement).

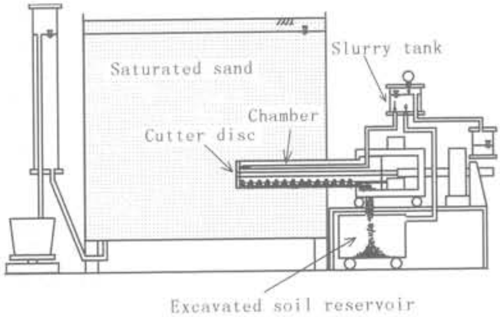


Figure 8. Miniature slurry shield machine and sand container.

dimension of the container was 1400 ×1600 × 1400 mm. The hydraulic jack was equipped at the top of soil container, which could press on the ground surface. The surface pressure was acted to obtain the magnitude of 98 kPa at the bottom of soil container for all the tests. The miniature slurry shield machine was driven from one side wall to the other wall, whose diameter was 215 mm. A schematic view of the shield model test apparatus can be seen in Figure 8. The function of the miniature shield is equivalent to that of the actual slurry shield. The shield model was always pushed forward in the saturated silica sand #6 ($\rho_s$ = 2.56 g/cm$^3$, $D_{50}$ = 0.23 mm) using 12% bentonite slurry at a driving velocity of 1 cm/min. and cutter rotation of 1 rpm. These execution conditions were similar to that of actual slurry shield. The specific gravity of 12% bentonite slurry was 1.063 and the funnel viscosity (500cc/500cc) was 31 sec.

Figures 9(a)-(b) present the locations of laboratory ground movement measuring device. The miniature slurry shield machine driving was carried out to investigate the influence of the magnitude of slurry pressure on the ground displacement during shield machine driving. The soil displacement, earth pressure and pushing pressure on the cutting face were measured while using a range of face slurry support pressures. The amount of excavated soil during machine driving was also measured.

### 3.2 *Results of the model tests*

The relationships between vertical displacement in the centre of the shield and shield driving distance under three cases of different slurry pressure are shown in Figures 10(a)-(b). The vertical displacement of Figure 10(a) was measured at the location of 1D (D: diameter of tunnel =215 mm) above the tunnel crown and that of Figure 10(b) was

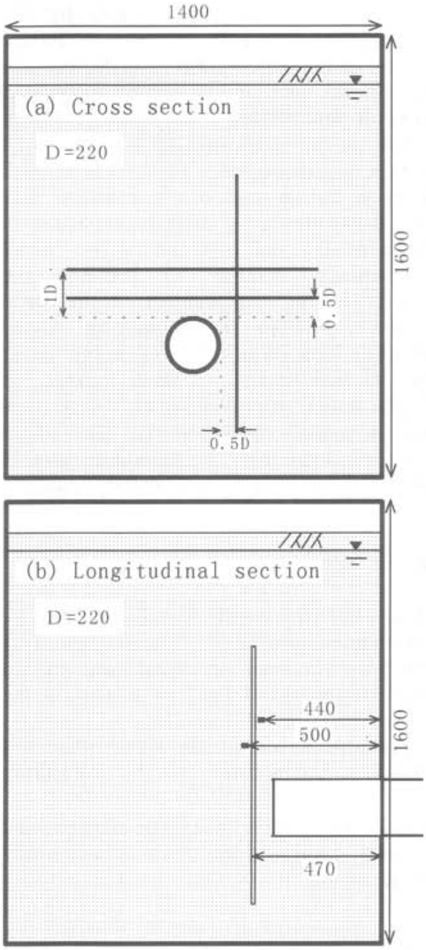
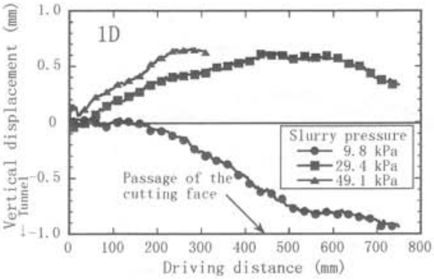


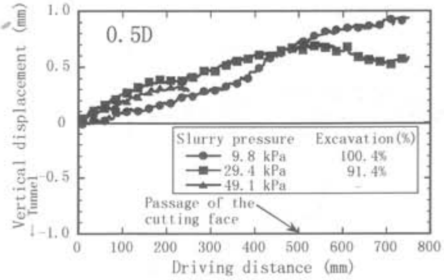
Figure 9. Locations of laboratory ground movement measuring device.

measured at the location of 0.5 D above the tunnel crown (see Figure 9(a)). The values of excavation volumes during machine driving are shown in Figure 10(b). As can be seen in these figures, for large magnitudes of slurry pressure, the soil was displaced upward.

The relationships between lateral displacement in the centre of the shield and shield driving distance under the three cases of slurry pressure are shown in Figure 11. The lateral displacement was measured at the location of 0.5D beside the tunnel spring line (see Figure 9(a)). As can be seen in the figure, the lateral inflow of the soil was observed before the arrival of the machine face regardless of the magnitude of slurry pressure. It can be thus concluded that the excavated soil is taken into the machine from the lateral ground rather than upper ground during shield driving.



(a) At the location of 1D above the tunnel



(b) At the location of 0.5D above the tunnel

Figure 10.Relationship vertical displacement and the magnitude of slurry pressure.

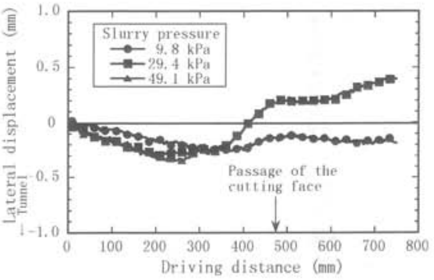
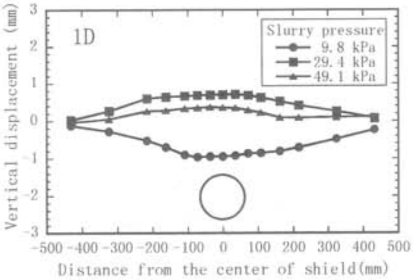


Figure 11.Relationship lateral displacement and the magnitude of slurry pressure(0.5D beside the tunnel spring line).

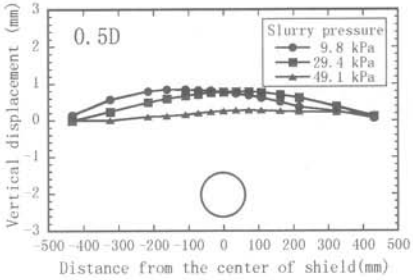
## 4 DISCUSSION OF THE MEASURED VALUES IN MODEL TESTING

These model tests were conducted on condition that the flexible metal plate was embedded initially in the horizontal position. Accordingly, the validity of above-measured values is considered on the basis of the magnitude and distribution of ground displacement.

The maximum measured ground displacement is extremely small, less than 0.9 mm. Therefore, as



(a) At the location of 1D above the tunnel



(b) At the location of 0.5D above the tunnel

Figure 12.Distribution of vertical displacement in cross-sectional direction.

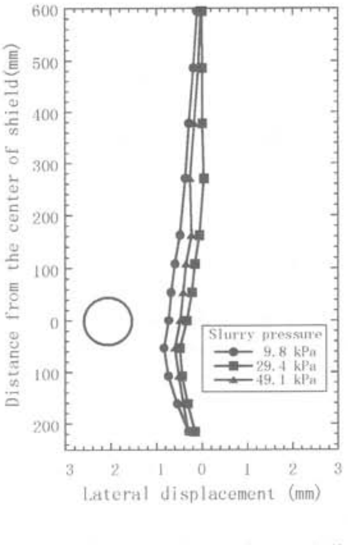


Figure 13.Distribution of lateral displacement in cross-sectional direction (0.5D beside the tunnel spring line).

mentioned in Section 2, it is conceivable that the ground displacement is able to be measured by the laboratory ground movement measuring device.

However, in the case of localization of ground displacement, it may become a significant problem in the accuracy of this measuring device. Figures 12 (a)-(b) present the distribution of vertical ground displacement at the passage of the machine face obtained from the measuring devices embedded in the locations of 1D and 0.5D above the tunnel crown respectively. Figure 13 presents the distribution of lateral displacement at the same situation obtained from the measuring device embedded at the location of 0.5D beside the tunnel spring line. As can be seen in these figures, the ground displacement takes place over a wide area, not locally. It is thus concluded that the ground displacement obtained from the laboratory ground movement measuring device is sufficiently reliable.

## 5 CONCLUSIONS

It is concluded from this experimental study that:

1. A laboratory ground movement measuring device has been produced for measuring ground displacement during shield machine driving in the laboratory.
2. The rounded shape of the metal plate has greatly improved the accuracy of this measuring device.
3. The excavated soil is taken into the machine from the lateral ground rather than upper ground during shield driving.

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