Study on the mechanism of friction between an underground structure and sandy ground

Shun Manabe i), Munehito Endo ii), Mitsuhiro Nakamura iii) and Kazuhide Komiyama iv)

i) Graduate Student, Department of Civil and Environmental Engineering, Chiba Institute of Technology, 2-17-1 Tsudanuma, Narashino, Chiba, 275-8588, Japan.
ii) Lecturer, Department of Civil and Environmental Engineering, Chiba Institute of Technology, 2-17-1 Tsudanuma, Narashino, Chiba, 275-8588, Japan.
iii) Engineer, Uemura engineering co., Ltd., 2-30-7 Hiyoshi-cho, kokubunji, Tokyo, 185-0032, Japan.
iv) President, Professor, Chiba Institute of Technology, 2-17-1 Tsudanuma, Narashino, Chiba, 275-8588, Japan.

ABSTRACT

When vehicles travel through a tunnel or when water flows through it, the gross weight of a tunnel and pressure of the earth acting on the bottom of the tunnel simultaneously increase. This change in earth pressure may induce risks such as ground settlement and ground failure. Additionally, the change in the stress state in the vicinity of an underground structure influences the friction between underground structure and the ground to a certain extent. In previous work, authors evaluated surface friction calculated from residual earth pressure at the bottom and lateral earth pressure at the sidewall of an underground structure model that were associated with changes in the weight of the model using laboratory tests. They concluded that residual earth pressure at the bottom corresponded to surface friction acting on the sidewalls of the model. In this study, the earth pressure acting on the bottom and the lateral earth pressure acting on the sidewall of the underground structure model were measured with change in the weight and uplifting of the model. We examined the mechanism of the surface friction between the underground structure and the sandy ground. The results showed that the earth pressure acting on the bottom was affected by the self-weight of the structure as well as the frictional forces acting on the surface of the structure.

Keywords: tunnel, friction, sandy ground, earth pressure, model test

1 INTRODUCTION

The self-weight of an underground structure such as a tunnel acts on the ground below the structure. When vehicles travel through a tunnel or water runs through it, the gross weight of a tunnel and the earth pressure acting on the bottom of the tunnel simultaneously increases. This change in the earth pressure may induce risks such as ground settlement and ground failure. When we consider the force equilibrium acting on an underground structure in the vertical direction, the downward forces due to overburden and self-weight of the structure are balanced by the upward forces due to frictional forces between the structure surface and the surrounding soil. These frictional forces possibly influence stress in the ground underneath the structure to a certain extent.

Nakatsuka et al. (2016) investigated earth pressure using a small-scale square-shaped model of an underground structure with pressure sensors on the bottom of the model and on the sidewalls. They measured the earth pressure acting on the bottom with changes in the weight of the model in shallow sandy soil and evaluated the frictional force between the surfaces of the sidewalls of the model and the ground (hereafter called surface friction) by computing from the residual earth pressure that acted on the bottom of the model. However, because of small size of the model, the resultant earth pressure was not adequate to identify the mechanism of surface friction based on change in the weight.

Manabe et al. (2018) conducted an identical experiment using a rectangular-shaped tall model, so that the earth pressure acting on the bottom of the model could be increased. They measured earth pressures acting on the bottom and the sidewalls of the model for different friction characteristics of the sidewall surfaces of the model. Then, they evaluated the surface friction due to change in the model weight from two different methods. The method by Nakatsuka et al. (2016) was used to compute the residual earth pressure at the bottom and the other was used to compute the lateral earth pressure measured at the sidewalls. They noted that surface friction could be evaluated using residual earth pressure at the bottom by comparing computed surface frictions between two methods. Additionally, they reported surface friction possibly influenced the earth pressure acting on the bottom of the underground structure with change in the weight of the structure.
The present study is an extension of previous work. We investigated whether surface friction could be evaluated by resistance force against the uplifting displacement of a structure model. The earth pressure at the bottom and the lateral earth pressure at sidewalls were measured on an underground structure model having different friction characteristics of sidewall surfaces. Subsequently, surface friction induced by earth pressure changes due to the uplifting displacement was calculated and compared with the resistance force of the model. Additionally, we compared the surface friction calculated from the residual earth pressure acting at the bottom with the resistance force of the model and investigated the mechanism of the surface friction between the underground structure and the sandy ground. In another experiment, the structure model was subjected to cyclic changes in the weight of the model. The results obtained from this experiment revealed that surface friction considerably affected the behavior of earth pressure acting at the bottom with cyclic changes in the weight of the model.

2 LABORATORY INVESTIGATION

2.1 Apparatus for model tests

The laboratory test was conducted in a rectangular soil tank which had inner dimension of 1500 mm × 1000 mm × 100 mm (length × height × width). An acrylic plate with a thickness of 150 mm was attached in front of a soil tank. The acrylic plate was reinforced with steel square tubes to prevent warping of the plate from the weight of the sand inside of the tank. The model ground was prepared using dry silica sand #8 filled by free-fall in the soil tank.

A box-type underground structure model with an open top and dimensions of 270 mm × 515 mm × 90 mm was used. Two earth pressure sensors at the bottom and one sensor at each sidewall were installed on the model. Figure 1 depicts the dimensions of the model and the locations of earth pressure sensors. Materials, a Teflon sheet and sand paper, with different friction characteristics were used to change friction between the sidewalls of the model and ground. The experimental uplift apparatus comprised a load cell, a displacement sensor and a loading device. During the uplift test, the uplift force and displacement of the structure model were measured by this apparatus.

2.2 Experimental procedure of model tests

The experimental procedure is presented in Fig. 2. In Step 1, the underground structure model was placed on the model ground prepared inside the soil tank and then measurement of earth pressure on the model was initiated. In Step 2, silica sand #8 was placed in the soil tank and inside the model by pouring the soil using a sieve till the top of the model. In Step 3, after placing the sand in the soil tank, it was untouched for 60 min to ensure the stable response of the earth pressure sensors. In Step 4, the sand inside the model was removed and soil was untouched for 30 min. In Step 5, the model was moved upward using the uplift apparatus, and the uplift force, displacement and earth pressure acting on the model were measured. In Step 6, measurements were also conducted prior to the termination of the experiment.

Fig. 1. Geometry of underground structure model and location of earth pressure sensors.

Fig. 2. Experimental procedure.
2.3 Coefficient of Friction between the underground structure model and soil

Materials, a Teflon sheet and sand paper, with different friction characteristics were attached on the sidewalls of the underground structure model in the present study. The coefficient of friction test is conducted to determine the coefficient of friction for sand paper and the Teflon sheet. Sand paper and Teflon sheet were attached to the square plate test pieces of 100 mm × 100 mm. The test pieces were mounted on an inclined plate whose surface was uniformly coated with No. 8 silica sand. The angle of incline could be changed by changing the height of one of the ends of the inclined plate using a jack. Figure 3 depicts the apparatus used for the coefficient of friction test.

First, a test piece was placed on the inclined plate and the angle of incline was gradually increased by elevating the height at one end of the inclined plate. When the test piece began sliding down, the angle of incline θ was measured and the coefficient of incline μ was estimated as tanθ. For each test piece, the test was repeated three times and the coefficient of friction μ was determined as the average value of these three measurements. The test results are presented in Table 1. The values of μ for sand paper and the Teflon sheet were 0.708 and 0.467, respectively.

2.4 Estimation of resultant forces of earth pressure

The resultant force acting on the bottom of the model P_r was obtained from the earth pressure σ_r acting on the bottom which was the average of the earth pressure measured by the two sensors at the bottom. On the other hand, the resultant force acting on the sidewall of the model P_h was obtained from the lateral earth pressure σ_h acting on the sidewall which was the average value of the earth pressure measured by the two sensors at the two sidewalls. For the calculation of P_h, the earth pressure was assumed to be uniformly distributed over the surface of the sidewall as indicated in Fig. 4.

The resultant force acting on the bottom of the model P_r was calculated using Eq. (1).

\[ P_r = \sigma_r \times A \times 10^3 \text{ (N)}, \tag{1} \]

where \( \sigma_r \) was average earth pressure acting on the bottom of the model (kN/m^2) and \( A \) was the area of the bottom surface of the model (m^2).

The resultant force acting on the sidewall of the model P_h was calculated using Eq. (2).

\[ P_h = 2 \times \frac{H}{H_m} \times \sigma_h \times H \times W \times 10^3 \text{ (N)}, \tag{2} \]

where \( \sigma_h \) was the average lateral earth pressure acting on the sidewall of the model (kN/m^2), \( H \) was the height of the model (m), \( W \) was the width of the model (m) and \( H_m \) was the depth of the earth pressure sensor on the sidewall of the model (m).

3 TEST RESULTS

The test result for sand paper attached on the two sidewalls of the model (hereafter called sand paper) is shown in Fig. 5. The behaviour of the average earth pressure \( \sigma_r \) acting on the bottom and the average lateral earth pressure \( \sigma_h \) acting on the sidewall of the model is presented from Step 1 to Step 6 (Fig. 2). When the model was placed on the model ground (Step 1), \( \sigma_r \) was 1.29 kN/m^2, which corresponded to the weight of the model. In Step 2, \( \sigma_r \) and \( \sigma_h \) gradually increased while placing No. 8 silica soil in the soil tank and inside the model. During Step 3, \( \sigma_r \) and \( \sigma_h \) remained stable. In Step 4, when the sand inside the model was removed, that value of \( \sigma_r \) was not the same as that in Step 1 (1.29 kN/m^2) and indicated a residual earth pressure of 4.78 kN/m^2. On the other hand, \( \sigma_h \) remained 1.41 kN/m^2 before and after the removal of sand inside the model. In Step 5, i.e., the uplift test (Step 5), both \( \sigma_r \) and \( \sigma_h \) simultaneously became zero indicating that the model began moving upward.

Similarly Fig. 6 shows the behaviour of \( \sigma_r \) and \( \sigma_h \) from Step 1 to Step 6 for the Teflon sheet attached on two the sidewalls of the model (hereafter called Teflon sheet).
sheet). When the model is placed on the model ground (Step 1), $\sigma_r$ was 1.17 kN/m$^2$, which was very close to the value for Case sand paper (1.29 kN/m$^2$). In Step 2, $\sigma_r$ and $\sigma_h$ gradually increased while placing the soil in the soil tank and inside the model, which was similar to what occurred with Case sand paper. In Step 4, the residual earth pressure was 2.33 kN/m$^2$ after removing sand inside the model (1.17 kN/m$^2$ was the value at Step 1). However, $\sigma_h$ remained 1.10 kN/m$^2$ before and after removal of the sand inside the model. In Step 5, i.e., the uplift test, both $\sigma_r$ and $\sigma_h$ simultaneously became zero indicating that the model began moving upward.

Figure 7 shows the resultant forces acting on the bottom of the model $P_r$ and on the sidewall of the model $P_h$ for Case sand paper calculated from $\sigma_r$ and $\sigma_r$ from Step 1 to Step 4, as shown in Fig. 5. The values of $P_r$ and $P_h$ were calculated using Eqs. 1 and 2, respectively. In Step 1, the value of $P_r$ was 31.35 N after the placement of the model. In Step 4, after removing sand from inside the model, the value of $P_r$ became 116.15 N as the resultant force due to the residual earth pressure, while the value of $P_h$ remained the same i.e., 156.54 N.

Figure 8 shows the behaviours of $P_r$ and $P_h$ and the uplift force and displacement of the model from Step 4 to Step 6 in the uplift test for Case sand paper. As observed in Step 5, the uplift force increases as soon as both $P_r$ and $P_h$ began to decreasing. When the uplift force reached the maximum value, i.e., $P_m = 119.93$ N, $P_r$ and $P_h$ became almost zero and then the displacement of the model occurred in the upward direction.

Similarly for Case Teflon sheet, $P_r$ and $P_h$, which are calculated from Eqs. 1 and 2 from Step 1 to Step 4, are shown in Fig. 9. The value of $P_r$ was 28.43 N after the placement of the model. Additionally, after removing sand from inside the model (Step 4), the value of $P_r$ became 56.62 N as the resultant force of residual earth pressure and the value of $P_h$ became 122.13 N.

Figure 10 shows the behaviours of $P_r$ and $P_h$ and the uplift force and displacement of the model from Step 4 to Step 6 in the uplift test for Case Teflon sheet. The uplift force increased as soon as both $P_r$ and $P_h$ began decreasing. When the uplift force reached the maximum value, i.e., $P_m = 89.02$ N, $P_r$ and $P_h$ became almost zero and then displacement of the model occurred in the
upward direction. The overall trend observed for Case Teflon sheet was quite similar to that of Case sand paper.

4 MECHANISM OF THE SURFACE FRICTION AND ITS EFFECT ON EARTH PRESSURE ACTING ON THE BOTTOM OF THE UNDERGROUND STRUCTURE

The resultant force acting on the bottom of the model $P_r$ after removing sand from inside the model (Step 4) was defined as the resultant force due to the residual earth pressure $P_y$. The values of $P_r$ calculated from Eq. 1 were 116.15 N for Case sand paper and 56.62 N for Case Teflon sheet. Next, the surface friction $P_f$ between the sidewall of the model and ground was computed by the resultant force acting on the sidewall of the model $P_h$ multiplied by the coefficient of friction $\mu$. The obtained values of $P_f$ were 110.83 N for Case sand paper and 57.03 N for Case Teflon sheet. Additionally, the maximum uplift forces $P_u$ of the model at Step 5 were 119.93 N for Case sand paper and 89.02 N for Case Teflon sheet. The maximum uplift force of Case sand paper, whose coefficient of friction was higher than that of the Teflon sheet, was obviously greater than that of Case Teflon sheet. Here, these uplift forces included the self-weight of the model.

To evaluate the surface friction between the sidewall of the model and ground, we compared the calculated values of $P_s$, $P_f$ and $P_r$ (Table 3). The values of $P_s$, $P_f$ and $P_r$ were almost identical for Case sand paper, while the values of $P_s$ and $P_f$ were 60% of that of $P_r$ for Case Teflon sheet. This indicated that the surface friction for Case Teflon sheet was lesser than that for Case sand paper and therefore, the resisting force acting on the sidewalls became small. As the result, upward movement of the model (due to buoyancy) was induced after removing sand in Step 4 and then less earth pressures acting on the bottom and lateral earth pressure acting on the sidewall were generated. In the current experiment, the possibility that surface friction between the model and ground could be evaluated from the resultant force due to the residual stress $P_y$ because $P_s$, is approximately equal to $P_y$. Additionally, the uplift force of the model $P_u$ could be considered as the maximum possible static friction force acting on the model.

Figure 11 shows the behaviours of $\sigma_r$ and $\sigma_h$ from Step 2 to Step 4 repeated three times. Each time in Step 2, the largest $\sigma_r$ displayed a tendency to decrease with the repetition of steps, while $\sigma_h$ was not affected by the repetition of the steps and remained the same. Each time in Step 4, after removing sand from inside the model, $\sigma_r$ became smaller instead of indicating the same value as the self-weight of the model with the repetition of steps. Therefore, earth pressure acting on the bottom of the underground structure was strongly influenced by the self-weight of the structure as well as the frictional forces acting on the surface of the structure.

![Fig. 9. Behaviour of resultant forces $P_r$ and $P_h$ from Step 1 to Step 4 for Case Teflon sheet.](image)

![Fig. 10. Behaviour of resultant forces $P_r$ and $P_u$, uplift force and displacement of the model from Step 4 to Step 6 for Case Teflon sheet.](image)

![Fig. 11. Behaviour of earth pressures $\sigma_r$ and $\sigma_h$ from Step 2 to Step 4 repeated three times for Case Teflon sheet.](image)

|                  | $P_r$ (N) | $P_f$ (N) | $P_u$ (N) |
|------------------|-----------|-----------|-----------|
| Sand paper       | 116.15    | 110.83    | 119.93    |
| Teflon sheet     | 56.62     | 57.03     | 89.02     |

Table 2. Comparison of $P_r$, $P_f$ and $P_u$.
5 CONCLUSIONS

In the present study, we evaluated the surface friction between a model and the ground by calculating residual earth pressure acting on the bottom and the resistance force against the uplift displacement of the model. Additionally, we considered the mechanism of surface friction in sandy soil. Results obtained from the laboratory test revealed that surface friction could be estimated from the residual earth pressure simultaneously acting on the bottom of the model. Moreover, we received clarity that earth pressure acting on the bottom of an underground structure was affected by surface friction acting on the surface of the structure as well as the self-weight of the structure.

REFERENCES

1) Manabe, S., Endo, M., Komiya, K. and Nakamura, M. (2018): Study on the friction of soil acted on the lateral surface of a rectangular tunnel in sandy ground, Proc. 73th Annual Meeting of the Japan Society of Civil Engineers, III-578, 1153-1154 (in Japanese).

2) Nakatsuka, R., Endo, M., Komiya, K., Koyama, Y. and Kodama, N. (2016): Laboratory model test on the friction between underground structure and soil in sandy ground, Proc. 71th Annual Meeting of the Japan Society of Civil Engineer, III-077, 153-154 (in Japanese).