Experimental study on the effect of preloading on the horizontal displacement of steel sheet pile walls

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ABSTRACT

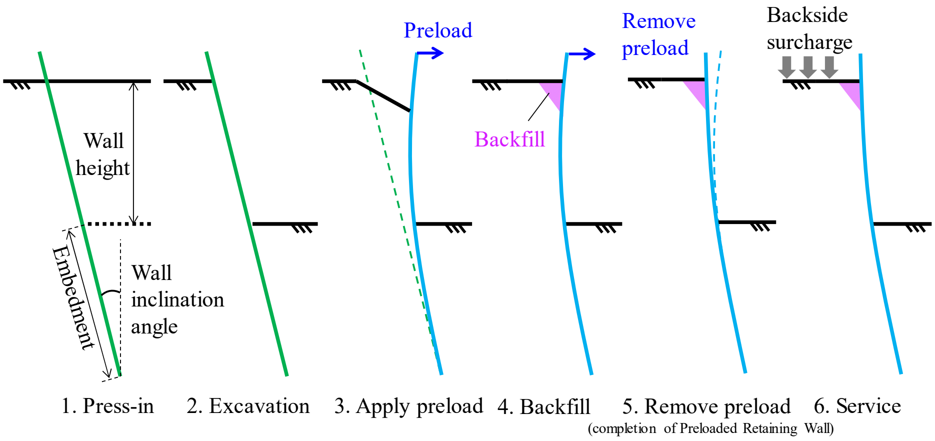
Embedded cantilever retaining steel sheet pile walls are constructed using high-quality, factory-manufactured sheet piles with uniform properties. The interlocks between adjacent steel sheet piles provide a high cutoff. However, as steel sheet piles are relatively flexible, they are susceptible to deflection. To reduce deflection, additional structures such as beams and anchors are sometimes used in combination. Preloaded Retaining Walls have been developed to take advantage of the flexibility of steel sheet piles. Preloaded Retaining Walls perform well against backside surcharge acting during service and provide high deflection control. After the sheet pile wall is installed with an inclination angle and the excavation is completed, a horizontal preloading is conducted by applying a horizontal preload to the top of the wall to displace it to the excavation side. The horizontal preloading gives a loading history to the ground on the excavation side and increases the stiffness. In addition, it provokes an elastic restoring force in the sheet pile wall to hold the backside ground. Although the high effectiveness of horizontal preloading has been confirmed in a field test, the method of applying horizontal preload presents challenges, so an alternative method could be vertical preloading. Model experiments were carried out to confirm the effectiveness of vertical preloading. This paper reports the results of the model experiments and summarizes the effects of the different methods of preloading on the deflection of the wall under a backside surcharge in service.

Keywords: *Steel sheet pile, Embedded cantilever retaining wall, Preloading, Surcharge, Model test*

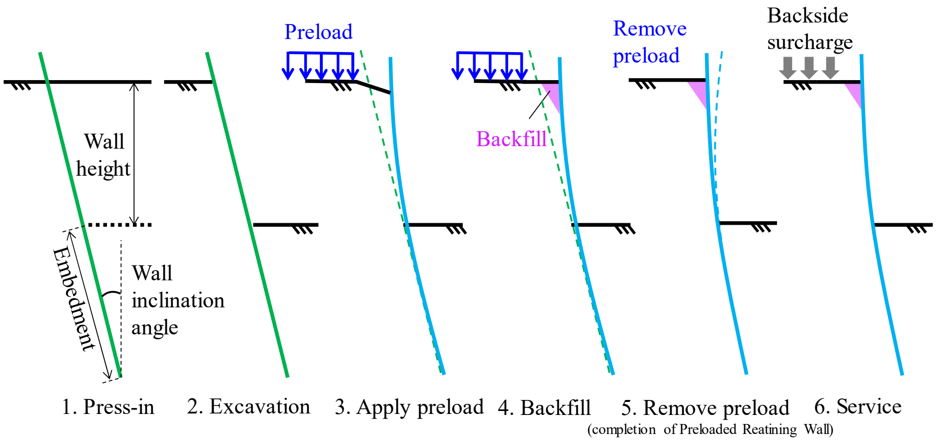
1. Introduction

In excavation works, earth retaining walls are constructed to prevent ground collapse and landslides in the surrounding area (e.g., Clayton, C.R.I., et al., 2013). This method suppresses deflection due to the ground resistance of the embedment and is characterized by its ease of construction and excavation work (JASPP and ACTEC, 2017). The steel sheet pile method uses factory-manufactured steel sheet piles, so walls with uniform material properties and strength can be constructed (IPA, 2021). In addition, the joints between adjacent sheet piles are highly cutoff (JASPP, 1993). Steel sheet piles are also widely used as temporary earth retaining walls because they are suitable for repeated use. However, the embedded cantilever retaining walls, where the top of the wall is the free end, are subject to more significant deflection in the steel sheet pile method, which is a highly flexible material. For this reason, a combination of shoring, such as struts and anchors, is used.

In recent years, improvements in construction technology have enabled raking sheet pile walls to be installed more easily, and in Japan, a design method has been proposed by Maeda et al., 2021. In this method, instead of constructing the earth retaining wall vertically,



a) Horizontal preloading



b) Vertical preloading

Fig. 1 Construction procedure of Preloaded Retaining Wall

the earth retaining wall is inclined to reduce earth pressure and wall deflection, thereby eliminating or reducing the need for shoring. There are also changes in the use of steel sheet pile walls, such as the development of sheet pile foundations (Nishioka et al., 2009), where steel sheet pile walls used as temporary works during excavation are integrated with existing footing foundations and used in the permanent structure.

The Preloaded Retaining Wall, a new development concept in the use of steel sheet pile walls, is an earth retaining wall with high performance against backside surcharge and improved deflection control during service. The construction process is shown in Fig. 1.

(1) Installing the wall material into the ground at an angle.
(2) Excavating one side of the wall and constructing a raking wall.
(3) Preloading (the wall or the ground around the wall).
(4) Fill the gap created by the preloading by placing backfill material between the backside ground and the wall.
(5) Remove the preload.

The authors confirmed the usefulness of the Preloaded Retaining Walls, which are constructed by applying horizontal forces to the head of the top of the wall, through empirical tests (Ishihara et al., 2015). In the experiment, the horizontal force was applied by two struts and walers attached to the upper parts of the Preloaded Retaining Wall and a reaction wall, and two hydraulic jacks installed between the struts and a reaction wall. Applying the preload in the same way is challenging in terms of implementation. Therefore, a method of applying a vertical load equivalent to the backside surcharge acting at the time of service to promote consolidation settlement and stabilize the ground was investigated. It is unclear how the preload is determined and what effect it has in reducing deflection.

The paper reports the results of small-scale model tests in a 1G field, confirming the effectiveness of using vertical loads as preloads to reducing deflection, and discusses issues with existing design proposals on how for determining preloads.

2. Model tests

1) Apparatus

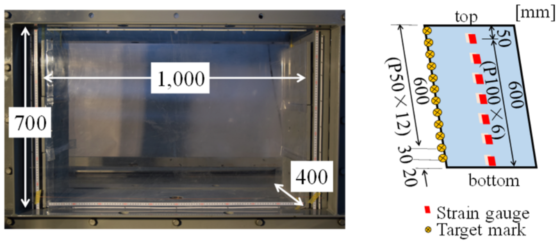
A small 1g model experiment test was carried out to replicate the process of excavation, and loading of the backside surface. As shown in Fig. 2, the size of the soil tank was 1,000mm×700mm×400mm. An acrylic board (650mm×398mm×5mm, E_A=2.3GPa) was used for the earth retaining wall, with strain gauges attached at seven points near the center of the soil layer. The markers were attached to the sides of the wall, and the deflection in the depth direction at each stage was measured from photographs.

2) Ground condition

For the experiment, soil layers were prepared using dry silica sand #6 (D_{50}=0.26mm, G_s=2.62, e_{max}=1.11, e_{min}=0.72) to achieve a relative density of roughly 50%. The particle size distribution of this sand is shown in Fig. 3. The earth retaining wall was installed after the bottom 50mm of the layer had been prepared. The soil layers on either side of the earth retaining wall were then prepared alternately. Dry sand was spread out to the left and right, and the thickness of the soil layer was leveled and pushed out, approximately 25mm at a time, with 50mm of black silica sand on the observation surface side only. The initial depth of the soil layer was 650mm.

3) Test cases

The test cases were conducted on a normal wall, which is a common earth retaining wall, a raking wall, and two types of preloaded walls. The conditions before excavation are shown in Fig. 4 and the model test cases are detailed in Table 1. The wall inclination angles tested were 0degrees and 10degrees, with a maximum excavation depth of 250mm. The types of preloads were (i) without preload, (ii) horizontal preload applied to the top of the top of the wall in the direction of excavation (as shown in Fig. 1-a), and (iii) vertical preload applied as an equally distributed load to the backside surface (Fig. 1-b).



a) Soil tank　　　　b) Model wall

Fig. 2　Model test apparatus

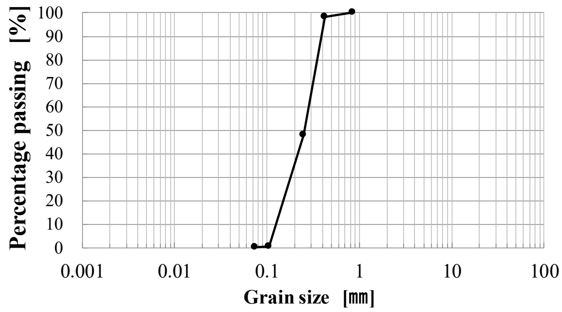


Fig. 3　Property and grain size accumulation curve of silica sand #6

a) Normal wall　　　　b) Raking wall (θ = 10 deg.)

Fig. 4　Side view of the model tests

Table 1　Test conditions

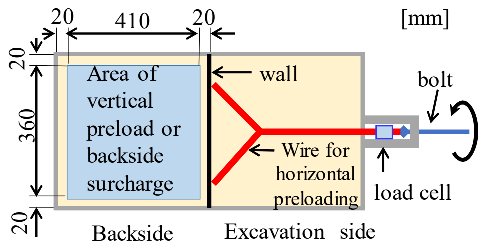
	Relative density [%]	Wall angle [degrees]	Excavation depth [mm]	Preloading
Case-N	53	0.3	250	without preload
Case-R	51	7.8	250	
Case-RH	56	10.3	250	Horizontal
Case-RV	52	9.8	250	Vertical

*N: Normal wall, R: Raking wall

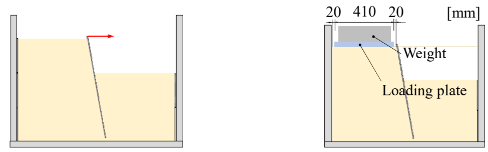
4) Layout

The right side of the retaining wall was used as the excavation side, and the left side was used as the backside. The horizontal preload was carried out by connecting two points at the head of the wall to a load cell with a y-shaped wire, as shown in Fig. 5-a, while the other end of the load cell was attached to a screw. Turning the screw applied tension which in turn applied horizontal tension to the edge of the wall. The load cell was made of steel plate laminated with strain gauges. The load was released by reversing the rotation of the screw.

The vertical preloading was the same method as the backside surcharge, and the backside surface was loaded vertically by weights. In the model tests, a styrene loading plate (410mm×360mm×30 mm) was placed 20mm away from the retaining wall as shown in Fig. 5-b, and weights were stacked on top of it to apply and remove the load in stages.



a) Plan view



(ii) horizontal preload

(iii) vertical preload / backside surcharge

b) Side view

Fig. 5 Loading methods

5) Test procedure

The construction of the wall was completed simultaneously with the preparation of the ground. Subsequently, excavation, preloading and backside surcharge were then carried out. A vacuum cleaner was used to suck up the sand for excavation. The nozzle of the vacuum cleaner was attached to an actuator located above the soil tank and moved at a constant speed. It was moved from the retaining wall to the side of the soil tank. Upon completion of the excavation, horizontal preload was applied and removed in case-RH, and vertical preload was applied and removed in case-RV. Finally, the backside surcharge was applied in all cases.

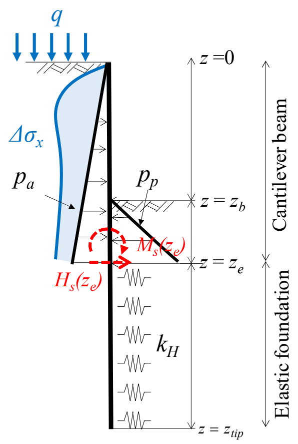


Fig. 6 Schematic diagram of calculation of deflection due to backside surcharge

6) Determination of the amount of preload

① Horizontal preload

Horizontal preload is the application of a load to the top of the wall during construction and its subsequent removal in order to demonstrate the deflection characteristics of the ground and the elastic resilience of the wall. The amount of the horizontal preload was set so that the wall deflection below the bottom of the excavation was equal to the deflection when the backside surcharge was applied. (Ishihara et al., 2015).

The elastoplastic method is often used in the design of embedded retaining walls (JASPP and ACTEC, 2017, JSCE, 2016). A schematic diagram of the calculation of the deflection during backside surcharge is shown in Fig. 6. The wall is assumed to be divided into upper and lower sections at the boundary of the plastic zone of the excavation side ground, where the upper section is a cantilever beam and the lower section is a beam on an elastic floor. When the backside surcharge is acting, the upper section is assumed to be a cantilever beam subjected to the earth pressure distribution with incremental horizontal stress due to the surcharge, and the combined horizontal force and moment acting on the lower section is assumed to be a beam on the elastic foundation. The coefficient of the subgrade reaction of the elastic floor, k_H, was determined by JASPP and ACTEC (2017). The coefficient of Coulomb earth pressure was used to calculate the earth pressure. As shown in Fig. 7, Boussinesq’s solution was used for the incremental stress on the ground due to the application of a backside surcharge (Ogawa et al., 2017). The equations are as follows.

$$p_A = K_A(\Sigma\gamma z + q) - 2c\sqrt{K_A} \quad (1)$$

$$p_P = K_P\Sigma\gamma(z - z_b) + 2c\sqrt{K_P} \quad (2)$$

$$K_A = \frac{cos^2(\phi+\theta)}{cos^2\theta\cos(\theta-\delta)\left\{1+\sqrt{\frac{\sin(\phi+\delta)\sin(\phi-i)}{\cos(\theta-\delta)\cos(\theta+i)}}\right\}^2} \quad (3)$$

$$K_P = \frac{cos^2(\phi-\theta)}{cos^2\theta\cos(\theta+\delta)\left\{1+\sqrt{\frac{\sin(\phi+\delta)\sin(\phi+i)}{\cos(\theta+\delta)\cos(\theta+i)}}\right\}^2} \quad (4)$$

$$\Delta\sigma_z = \frac{q}{\pi}(\beta + \sin\beta\cos\psi) \quad (5)$$

$$\Delta\sigma_x = \frac{q}{\pi}(\beta - \sin\beta\cos\psi) \quad (6)$$

p_A : active earth pressure
p_P : passive earth pressure
K_A : coefficient of active earth pressure
K_P : coefficient of passive earth pressure
ϕ : internal friction angle of the soil
c : cohesion of the soil
δ : wall friction angle $\left(\frac{1}{3}\sim\frac{2}{3}\right)\phi$
θ : wall angle
i : slope of background surface
$\Delta\sigma_z$: vertical stress increases due to the surcharge
$\Delta\sigma_x$: horizontal stress increases due to the surcharge
q : surcharge load
$\beta = \beta_2 - \beta_1$
$\psi = \beta_2 + \beta_1$

The wall deflection is determined from the equilibrium equation of these beams -method (1). The deflections are then determined assuming that the upper condition is changed to a concentrated load at the top of the wall - method (2). The horizontal preload is the load at which the load for which deflection under the excavation bottom of method (2) is equal to method (1).

Ishihara et al. (2015) used reaction walls and walers that were prepared and subjected to horizontal preload. The usefulness of this method in reducing deflection was confirmed. However, in the actual situation, it is not convenient to prepare a reaction wall, and a simpler method of applying preload needs to be investigated.

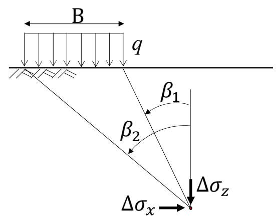


Fig. 7 Stress increases due to surcharge

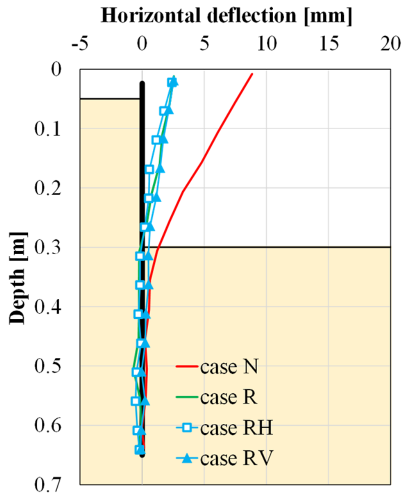


Fig. 8 Incremental horizontal displacement due to excavation

② Vertical preload

As mentioned above, the preload needs to be large enough to generate the deflection that occurs at the depth below the bottom of the excavation when the backside surcharge is applied. In the case of vertical preloading, a equal to or more than sufficient load than the design load should be applied at the construction stage to provide deflection that will cause displacement to increase soil strength. The model experiments were conducted by applying and removing the backside surcharge greater than the design load.

3. Results and discussion

1) Behaviour of the normal and raking walls during excavation without preloading

Fig. 8 shows the incremental deflection due to excavation. For the normal wall (case-N), the displacement of the top edge was close to 10mm, whereas for raking walls, the displacements were around 2.5mm in all cases. It was confirmed that the raking wall can reduce the amount of deflection during excavation.

Fig. 9 shows the results of comparing the moment distribution calculated from the strain gauges. Comparing the maximum values of the seven measured points, the case-R series (R's) showed values less than half that of case-N. In case-N, the maximum bending moment was -1,500N･mm at 75mm below the bottom of the excavation, whereas in case R's, the maximum bending moment was around -600N･mm at 175mm below the bottom of the excavation.

It was determined that all processes up to the completion of the excavation were the same and that the model experiment could be replicated. By inclination the retaining wall by approximately 10 degrees (case-R's), the deflection of the top of the wall due to excavation was reduced by 70% and the maximum bending moment was reduced by 50% compared to case-N. As the second derivative of the moment distribution is the distributed load, it can be inferred that the resultant force of the backside and excavation sides of the earth pressure acting on the raking wall decreases.

Fig. 10 shows the state of the earth retaining wall, including the wall angle. In addition to the difference in the combined earth pressure, the wall's weight promotes deflection in case-N after the excavation has formed the slip plane on the backside ground, whereas it resists deflection in case-R.

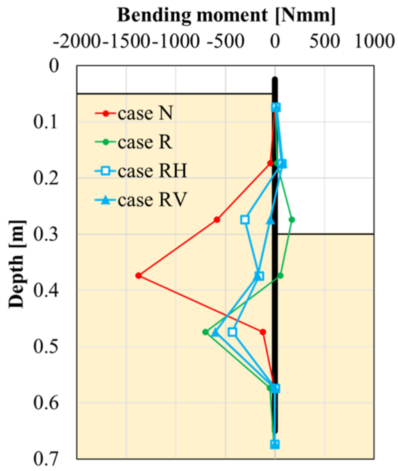


Fig. 9 Incremental bending moment due to excavation

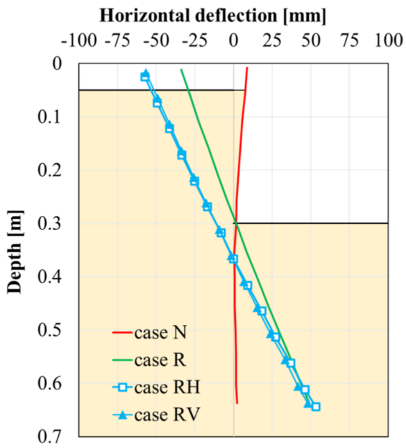


Fig. 10 Retaining walls after excavation

2) Behaviour of preloaded walls during construction (the application and removal of preload)

The preloads applied under the experimental conditions were the horizontal preload of 37N and the vertical preload of 4.6kPa. Fig. 11 shows the horizontal displacement of the design and applied values, and the removal preload. The horizontal preload was equal to the design load. Fig. 12 shows the incremental bending moment at the applied and removed preloads. In both cases there were a maximum value at the measurement point at a depth of 0.480m.

In Ogawa et al. (2017), it was reported that existing design concepts overestimate the estimated quantities when using Boussinesq's solution (e.g., Kusakabe, 2004). One reason for this may be that the incremental ground stresses estimated using Boussinesq's solution are taken into account from the backside surcharge. In this case, it is assumed that the ground is elastic, but in reality, it is a

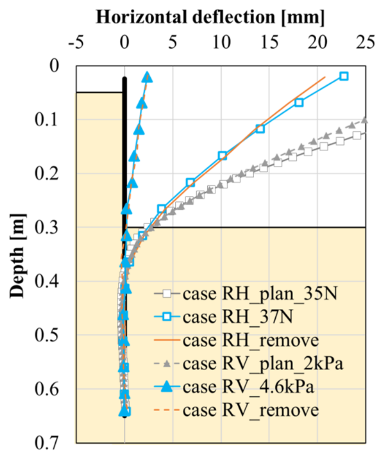


Fig. 11 Incremental wall deflection due to the application and removal of preload

loose sand layer, so local plastic zone failure may develop, resulting in a smaller incremental value of horizontal stress. When the preload was removed, in case-RH, the bending moment decreased below the depth at which the

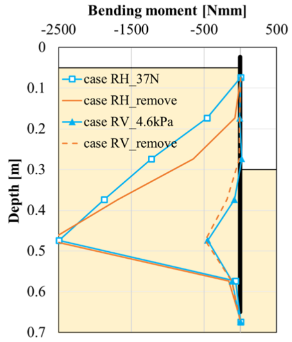


Fig. 12 Incremental bending moment due to the application and removal of preload

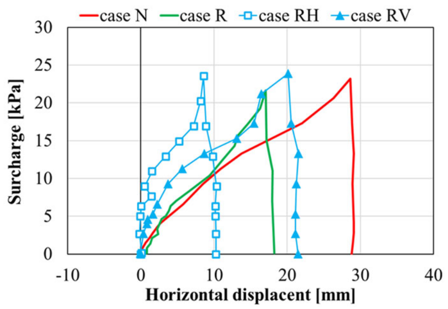
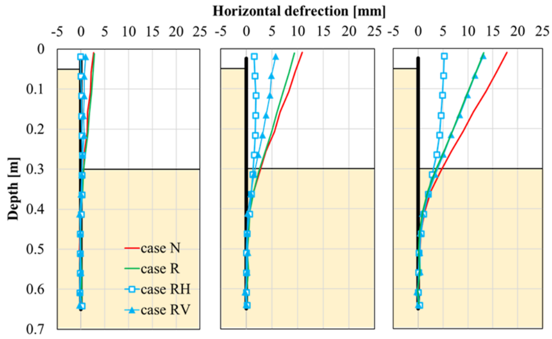
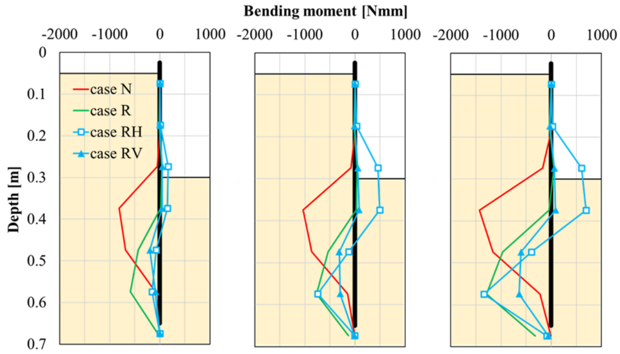


Fig. 13 Load-displacement curves during backside surcharge in service



a) 5kPa b) 10kPa c) 15kPa

Fig. 14 Incremental horizontal deflection due to the backside surcharge in service



a) 5kPa b) 10kPa c) 15kPa

Fig. 15 Incremental bending moment due to the backside surcharge in service

peak bending moment occurred, and the wall rebounded backward. On the other hand, in case-RV, the bending moment slightly increased below the depth where the peak bending moment occurred and no rebound occurred.

3) Behaviour of each wall due to backside surcharge in service

Next, the load- displacement curves for the cases where the backside surcharge is applied after the preload is removed are shown in Fig. 13. The vertical axis shows the incremental displacement of the top of the wall due to the surcharge. The initial angles of case-N and case-R without preload are almost the same, but the displacement suppression effect of case-R increases when the load exceeds 10kPa. In terms of the case-R's, the displacement suppression effect increases in the order of case-R (no preload), case-RV (vertical preload), and case-RH (horizontal preload). The slope of the load- displacement curves at a backside surcharge of 5kPa or less is about 10 times higher in case-RH and about 2 times higher in case-RV compared to case-R. In case-R and RV, the load-displacement curves overlap above 15kPa. The results showed that the influence could be expected up to about three times the preload.

Fig. 14 shows the deflection distributions for the backside surcharge of 5kPa, 10kPa, and 15kPa. Case-N and case-R showed mode 1 deflection, in which the deflection rotates around 0.5m vertically in the direction of excavation, and case-RH exhibited mode 2 deflection, in which the increment of the deflection after horizontal preloading and removal forms an inverted S-shaped curve. Fig. 15 shows the incremental bending moment due to the application of the backside surcharge. Case-N had a negative bending moment distribution, while in case-R's, the bending moment distribution took an inverted S-shaped curve. This is also consistent with the same bending moment distribution as in Takahashi et al. (2013). In order for the elastic resilience of the wall to hold backside ground, it is necessary to preload the wall so that the bending moment distribution has an inverted S-shaped distribution.

4. Conclusions

The Preloaded Retaining Wall is a new concept of embedded cantilever earth retaining wall that is expected to suppress the amount of deflection that occurs during the application of a backside surcharge in the service period. A small 1g model experiments were carried out to ascertain the effect of the preloading method on the deflection suppression effect during the application of a backside surcharge.

① Both horizontal and vertical preloads were found to be effective in reducing deflection.

② In the model test, the amount of deflection generated was approximately halved when the vertical preload and the backside surcharge were the same.

③ For horizontal preload, it was confirmed that the subsequent distribution of bending moments takes an inverse S-curve after the preloading and removal process. The adaptability of the estimation of deflection when horizontal preload is applied was also confirmed.

④ The incremental stresses in the ground at the application of backside surcharge were overestimated when the stresses in the ground were estimated using Boussinesq's solution and the deflections were determined. This needs to be improved in order to determine the design loads for the preload wall.

In order to construct preloaded retaining walls in a rational and practical design, it is necessary to accurately predict the impact of backside surcharge on retaining walls. Further research and study will continue, including long-term durability.

5. Acknowledgements

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