

Design and Construction of Inclined-Braceless Excavation Support Applicable to Deep Excavation

Dimensionnement et Construction du Support d'Excavation Incliné Sans Butons Applicable à une Excavation Profonde

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ABSTRACT: The inclined-braceless excavation support (IBES) construction method is characterized by allowing the reduction of retaining wall rigidity and omission of shoring because it reduces the earth pressure acting on the wall, compared with construction using vertical retaining walls. Thus, there are cases where inclined retaining walls are more beneficial in terms of workability and economy than vertical retaining walls, depending on the excavation depth or ground conditions. For the inclined-braceless excavation support construction method applied at open-cut (excavation depth of 9.6m) construction site, this paper presents results of centrifugal model experiments that reflected the actual excavation cross section, the design of the retaining walls in consideration of the inclination of the wall, applied construction method, and measurement results at the site.

RÉSUMÉ: On peut s'attendre à ce qu'une paroi de soutènement inclinée subisse une pression du sol moindre qu'une paroi verticale classique. Le Support d'Excavation Incliné Sans Butons (SEISB) pourrait donc offrir des avantages: un besoin de rigidité réduit et la disparation des étrésillons ou des ancrages. Selon la profondeur d'excavation et les conditions de sol, il peut aussi être plus efficace qu'un système vertical en termes de coût et de durée des travaux. Le présent document rapporte le cas d'un chantier où la méthode SEISB a été utilisée pour une excavation de 9,6m de profondeur: test en centrifugeuse sur un modèle de la coupe d'excavation du chantier, dimensionnement prenant en compte la pression du sol sur un support incliné, méthode de construction adaptée et réalisation des travaux.

KEYWORDS: Inclined-braceless excavation support, steel sheet pile, centrifuge model experiment, earth pressure

1 INTRODUCTION

According to earth pressure theory, the earth pressure acting on temporary earth retaining walls set up during excavation work is reduced when the earth retaining wall is reclined. However, earth retaining walls are generally installed vertically in consideration of workability and construction site limitations, and no earth retaining walls which utilized effect of reduced earth pressure for inclined retaining wall were implemented. Furthermore, deep excavation work requires shoring such as bracing or ground anchors for vertical earth retaining walls with high rigidity (Figure 1).

The inclined-braceless excavation support (IBES) construction method is characterized by allowing the reduction of wall rigidity and omission of shoring because it reduces the earth pressure acting on the wall, compared with construction using vertical retaining walls (Figure 2). Thus, there are cases where inclined retaining walls are more beneficial in terms of workability and economy than vertical retaining walls, depending on the excavation depth or ground conditions.

The authors have previously conducted centrifugal model experiments on inclined-braceless retaining walls using sand ground to examine earth pressure distributions and deformation behavior (Shimada et al. 2010, 2011) and quantitatively confirmed that the earth pressure acting on the retaining walls and deformation arising from excavation can be reduced by inclining the retaining walls.

This paper reports on centrifugal model experiments that reflected the excavation cross section at an actual scale construction site for the inclined-braceless retaining wall construction method to determine its suitability, the design of inclined-braceless retaining walls using reduced earth pressure by inclination of the wall, applied construction method, and measurement results at the site.

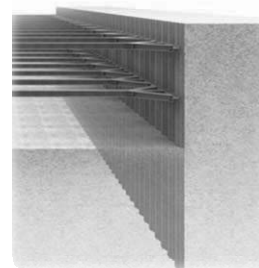


Figure 1 Vertical retaining wall

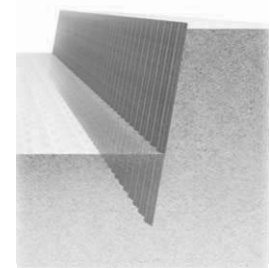


Figure 2. Inclined-braceless retaining wall

2 SUMMARY AND ISSUES OF CONSTRUCTION METHOD FOR INCLINED-BRACELESS RETAINING WALL

Cantilever retaining walls have been widely adopted to retain earth at relatively shallow excavation depths (3–4 m). Inclined-braceless retaining walls are an attempt to switch from the conventional concept of vertical retaining walls in order to reduce earth pressure and make it possible to apply cantilever retaining walls even at deeper excavation depths.

There are no application examples of temporary inclined retaining walls; design issues for the inclined-braceless retaining wall construction method include calculation of the earth pressure while considering the inclination of the retaining wall, and consideration of rollover not only to the excavation side but also to the back side in calculation of embedding of walls. Construction issues include the accuracy of the inclination angle set during retaining wall installation and the construction work cycle time. Centrifuge model experiments conducted to examine these design issues, the applied design

methods, and actual performance at construction sites where the design methods were implemented are described below.

3 CENTRIFUGE MODEL EXPERIMENT OF INCLINED-BRACELESS RETAINING WALL

3.1 Experiment method

A 1/33-scale model ground was prepared to develop excavation cross sections of applicable construction sites (Figure 3) for this experiment. A maximum centrifugal acceleration of 33g was loaded to examine deformation of the retaining wall and distribution of the earth pressure. Figure 4 shows an outline of the model ground. The dimensions of the soil container were 80 cm width × 50 cm height × 20 cm depth. The front side of the container was fabricated from an acrylic plate so that ground displacements could be measured. A Teflon sheet was attached between the soil container, including the acrylic plate, and the model ground to reduce friction. The depth of the model ground was developed with berm to a maximum of 29 cm, and the height of the retaining wall was 36 cm. The model ground is shown in Photo 1. The retaining wall was created assuming that the retaining walls would be made of steel sheet piles. A compact earth pressure gauge (6 mm dia., capacity of 1 MN/m²) was embedded at seven locations on the active side and at four locations on the passive side to measure the earth pressure acting on the wall surface. The retaining wall model was installed and then filled with dry Toyoura standard sand by the airdrop method to prepare the model ground. Excavation steps were simulated during the experiment by repeating the method of loading centrifugal acceleration after the prescribed excavation work was performed at a 1g site. Table 1 shows the experimental cases.

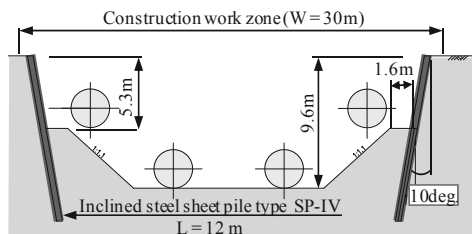


Figure 3. Cross-section of inclined-braceless retaining wall applied at site

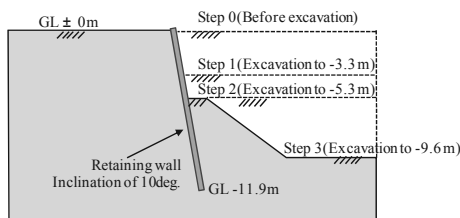


Figure 4. Outline of model ground.

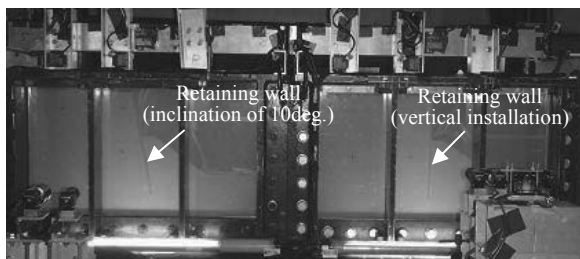


Photo 1. Model ground

Table 1: Experiment Cases

No.	Case 1	Case 2
Retaining wall conditions	Vertical	Inclined (inclination of 10 degree)
Retaining wall model	Made of aluminum, thickness of 7 mm	
Ground	Material: Toyoura standard sand (dry) Density: $\rho_d = 1.55 \text{ g/cm}^3$ Preparation method: Airdrop method	
Excavation steps	Step 0: Before excavation Step 1: Excavation depth of 3.3 m Step 2: Excavation depth of 5.3 m Step 3: Excavation depth of 9.6 m	

3.2 Experiment results

Figures 5 and 6 show the deformation behavior of the retaining wall due to excavation work. The displacements shown below were converted to actual-scale displacements by multiplying the experimental measurement results by 33. Figure 5 shows the displacement distribution of the retaining wall for each excavation stage. The horizontal displacement was larger at higher sections of the wall, and deformation occurred in the frontal incline with the lower section of the wall as the axis. Regardless of the excavation depth, the amount of horizontal displacement of the inclined walls was smaller than that of the vertically installed walls. Figure 6 shows the relationship between the excavation depth and horizontal displacement at top of the wall. The deformation increased in correlation to the depth; the displacement of the vertically installed wall was measured at the maximum excavation depth as 20 cm, whereas that of the inclined wall was about 14 cm. Thus, the experimental results confirmed that the amount of deformation was about 30% smaller with inclined walls.

Strain gauges were attached to the front and back surfaces of the wall in the direction of the depth at three locations in order to obtain the bending status of the wall. Figure 7 shows the depth distribution of the bending strain: the maximum value was obtained in the vicinity of the center of the wall regardless of whether the wall was inclined. The maximum bending strain was smaller with inclined walls than with vertically installed walls regardless of the excavation depth. The gap between the two was larger when the excavation depth was 9.6 m than when it was 3.3 m; the effects of inclining the wall were significant and evident.

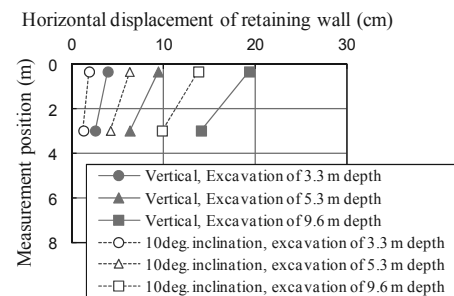


Figure 5. Horizontal displacement distribution of retaining walls

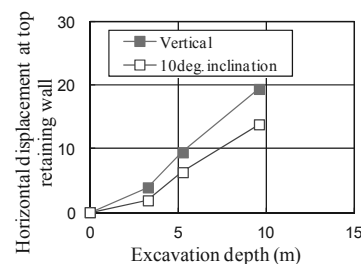


Figure 6. Relationship between excavation depth and horizontal displacement of retaining walls

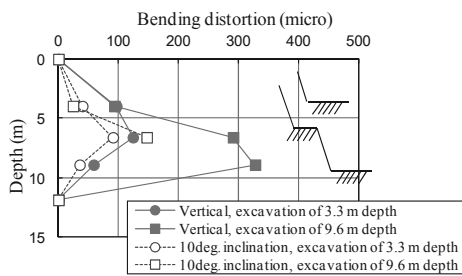


Figure 7. Bending strain distribution of retaining

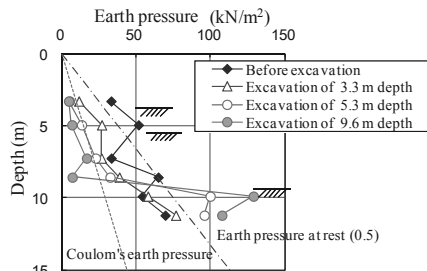


Figure 8. Earth pressure acting on wall surfaces - vertical retaining walls

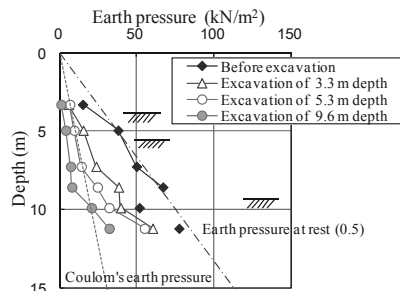


Figure 9. Earth pressure acting on wall surfaces - inclined retaining walls

Figures 8 and 9 show the depth distribution of the active earth pressure that acted on the wall. Although the measurement results for the vertically installed wall showed dispersions prior to excavation, the validity of the earth pressure measurements taken by this equipment were confirmed because they were approximately equal to the earth pressure at rest assuming $K_0 = 0.5$, as noted in the figure. The earth pressure decreased in the excavated sections and increased more than the earth pressure at rest in the embedded sections. The figure shows the Coulomb's earth pressure, where the friction angle of the retaining wall was considered to be $\phi/3$. The active earth pressure measured at the excavated sections was slightly smaller in distribution than the Coulomb's earth pressure. The earth pressure acting on the inclined wall decreased more than the earth pressure at rest regardless of depth. Thus, the acting pressure was smaller than that of the vertically installed wall, which confirmed that inclination of the wall contributed to the stability of the wall in terms of earth pressure as well.

4 DESIGN OF INCLINED-BRACELESS RETAINING WALL

4.1 Calculation method for earth pressure

Ground of the site (Figure 3) was a landfill comprised primarily of loose fine sand (layer thickness: 12 m, N-value: 3–5, and ϕ : 33°). The inclination of the retaining wall could not be considered in the conventional design of the temporary retaining walls, because the Rankine–Resal formula is generally applied to the active earth pressure used. The earth pressure calculation method with Coulomb's formula (Figure 10) used in the design of permanent retaining walls, which considers the inclination of the wall, was therefore applied. Its use was determined safe for design purposes because the earth pressure reduction effect was confirmed in the centrifugal model

experiments with inclined walls. Similarly, the Coulomb's earth pressure was adopted for the passive earth pressure.

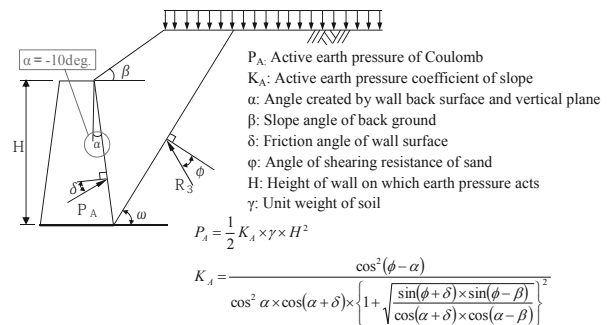


Figure 10. Active earth pressure calculation

4.2 Calculation method for embedding lengths

The embedding length was calculated using not only the “method for determining embedding length to maintain balance based on earth pressure” but also the “overall slippage including the retaining wall.” The circular slipping calculation (Figure 11) was performed to determine the embedding length so that both of the above methods were satisfied. The safety factor for the arc slipping calculation was set to 1.2.

4.3 Calculation of retaining wall displacements and stresses

The displacements and stresses that occurred with the retaining wall were calculated based on elasto-plasticity analysis, which evaluated the earth pressure and wall embedding length given in subsections 4.1 and 4.2 above, by considering the retaining wall as a finite length elastic beam and ground as an elasto-plastic spring (figure 12).

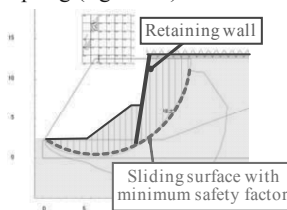


Figure 11. Verification on slipping stability

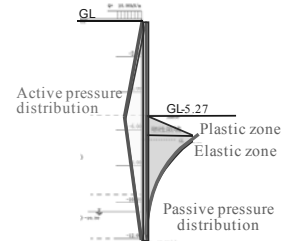


Figure 12. Elasto-plastic analysis

5 CONSTRUCTION WORK IMPLEMENTATION RECORD FOR INCLINED-BRACELESS RETAINING WALLS

5.1 Summary of applied construction sites

The construction sites where the inclined-braceless retaining walls were applied were located within premises used by existing electric power plant and new plant construction. Excavation work had to be performed to install two sets of water intake and water discharge steel pipes (each pipe with a diameter of 2800 mm) in a restricted construction work zone with a width of 30 m (Figures 3 and 13). The period of construction work, which included piping work, needed to be less than six months owing to adjustments that had to be made to accommodate the progress of the main unit construction work being performed at new electric power plant.

In order to satisfy the above conditions, the inclined-braceless excavation retaining wall construction method which reduces earth pressure by inclining the wall, was adopted as it requires no shoring, even when the excavation depth is deep. The retaining wall was fabricated from steel sheet pile type SP-IV, and the inclination of the retaining wall was set to 10 degree owing to restrictions imposed within the construction work zone and the excavation cross section necessary for piping work.

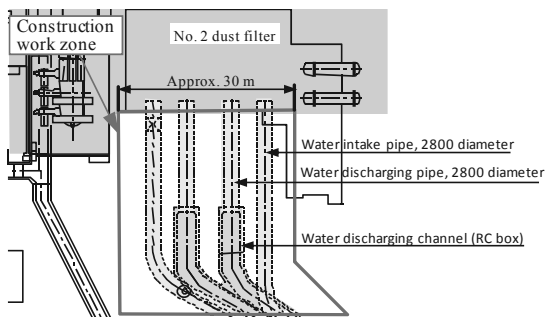


Figure 13. Construction work zone plan

5.2 Inclined-braceless retaining wall construction method

The steel sheet piles driven in at an inclination angle were installed in a manner similar to ordinary vertical installation: a silent piler was used combined with a water jet to reduce the insertion resistance. Because the piler was tilted according to the inclination of the piles being installed, an auxiliary cylinder was installed on the piler main unit to control the angle (Photo 2 and 3). The initial insertion until the piler was set on the piles used a blocking base (110 kN), similar to ordinary vertical installation. The top plate of the blocking base was inclined by 10 degree to accommodate the inclined installation of the piles (Photo 4). The inclination angle was monitored by infrared laser units installed at two locations aside from inclined finishing stake.

5.3 Comparison of onsite measurement results and design values

5.3.1 Earth pressure

The distribution of actual measurements for the earth pressure, which was taken by wall-surface-mounted earth pressure gauges at the time of the final excavation, indicated 20%–50% of the design values on the back side (active side) and 5% of the ultimate value on the excavation side (passive side) (figure 14). The setting method for coefficient of earth pressure (applying the Coulomb's formula) was considered to be valid because the gradient (equivalent to the earth pressure coefficient) up to GL-3m was roughly equal for the active earth pressure distribution. With regard to the passive earth pressure, the displacement of the retaining wall was small and the ground had a sufficient margin for resistance on the passive side.

5.3.2 Displacements and stresses of steel sheet piles

The maximum displacement during final excavation was 24.1mm, which was about 20% of the design value of 119.2mm (Figure 15). The maximum stress level of the steel sheet piles according to strain gauges was a tensile stress of 8.4N/mm², which is extremely small and about 8% of the design value of 103N/mm². Furthermore, the bending moment distribution obtained by converting the measurement data from the inclinometers was roughly the same as the bending moment distribution obtained from strain gauges.



Photo 2. Overall view of installation work



Photo 3. Auxiliary cylinder



Photo 4. Blocking base

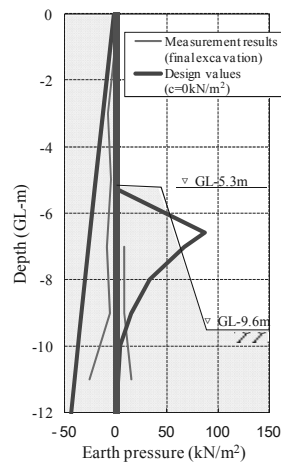


Figure 14. Earth pressure distribution comparison

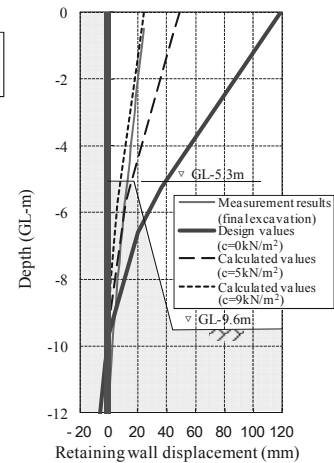


Figure 15. Retaining wall displacement

6 CONCLUSIONS

For the inclined-braceless retaining walls (inclination of 10 degree) with an excavation depth of 9.6 m in sand ground, the effects of earth pressure reduction and stability of retaining wall were verified by a centrifugal model experiment. A design method was developed that considers inclination of the wall by using the Coulomb's formula in elasto-plastic analysis so that inclined-braceless retaining walls can be adopted at actual construction sites. The actual measurement values taken onsite for the earth pressure acting on the retaining wall and the displacement and stress of the retaining wall both agreed with the design values. Thus, the safety of the retaining wall can be secured using the proposed design method. The inclined retaining wall construction method was used to realize a cantilever retaining wall without shoring despite a deep excavation depth of 9.6 m. Thus, excavation, piping, and building work can be completed in a short term and safely.

We will collect design and construction work track records for the inclined retaining walls under a variety of ground conditions for verification of evaluation methods for analysis models, soil parameters, and earth pressure, and cycle time of construction work, in order to establish more practical design and construction methods.

7 REFERENCES

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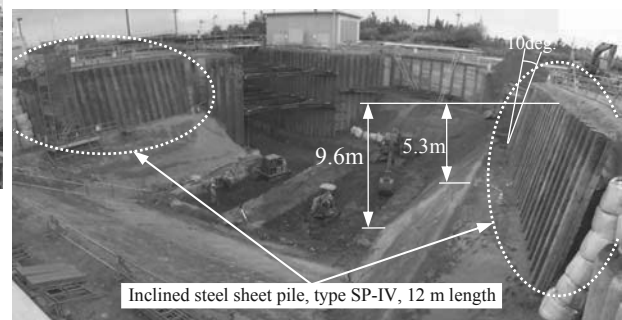


Photo 5. Overall view of excavation completed site