Geotechnical Aspects of Underground Construction in Soft Ground – Ng, Huang & Liu (eds)
© 2009 Taylor & Francis Group, London, ISBN 978-0-415-48475-6

Excavation with stepped-twin retaining wall: Model tests and numerical simulations

N. Iwata, H.M. Shahin, F. Zhang, T. Nakai, M. Niinomi & Y.D.S. Geraldni
Department of Civil Engineering, Nagoya Institute of Technology, Nagoya, Japan

ABSTRACT: Braced excavation using stepped-twin retaining wall is becoming popular in Japan. As it is a new technique used to prevent movements of double-elevated ground, mechanism of deformation due to excavation and change of stresses have not been fully understood. The design methodology of this technique is also not properly established. In this research, two-dimensional model tests are conducted to investigate the deformation mechanism of the ground and the earth pressure of the stepped-twin retaining wall. Numerical simulations with finite element method are also carried out for the same scale of the model tests. The aim of the research is to make clear the mechanism of the braced excavation using stepped-twin retaining wall and to establish an effective way to evaluating the mechanical behaviors of the retaining wall and the surrounding ground.

1 INTRODUCTION

In urban area, open excavation often cause problems to surrounding ground and adjacent structures. In practical daily design works, however, earth pressure is usually predicted by conventional methods such as a frame model together with Rankine's earth pressure theory. There is also no appropriate method to predict surface settlements of ground, which is usually predicted by empirical method and/or elastic finite element method. For braced excavation using stepped-twin retaining wall, conventional method cannot taken into consideration properly the influence of nearby structures as well as the construction sequence in evaluating the ground movements and the earth pressure.

In this research, two-dimensional (2D) model tests are conducted to investigate the deformation mechanism of the ground and the earth pressure of the stepped-twin retaining wall. Numerical simulations with finite element method are also carried out for the same scale of the model tests. In the finite element analyses, subloading t_{ij} model (Nakai & Hinokio 2004), is used in the analysis to model the ground material. This model can describe typical stress deformation and strength characteristics of soils such as the influence of intermediate principal stress, the influence of stress path dependency of plastic flow and the influence of density and/or confining pressure. Mass of aluminum rods is used in the model ground. Several patterns of the model tests are performed varying the length of the retaining wall and changing the distance between the two walls. The results of stepped-twin retaining wall are compared with the single retaining wall.

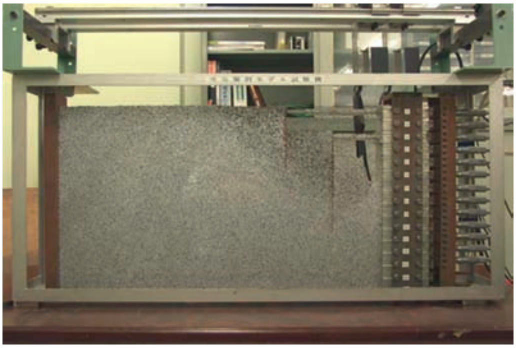


Figure 1. 2D Model test device.

2 OUTLINE OF MODEL TESTS AND NUMRICAL SIMULATIONS

2D Model tests and the corresponding numerical simulations of braced excavation using stepped-twin retaining wall, were carried out to make clear the mechanical behavior the problem. Figure 1 shows the outline of the 2D Model test device. Four cases of model tests with different length of outer retaining wall and different spacing of stepped-twin retaining walls were considered, as shown in Figure 3.

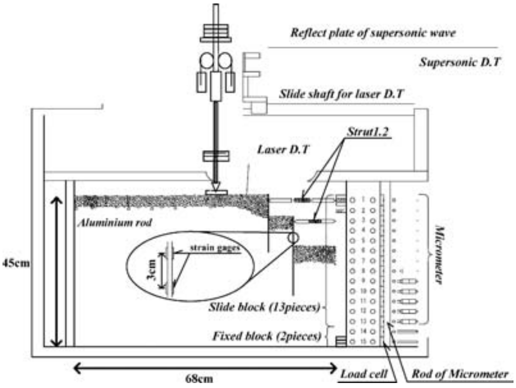


Figure 2. Outline of 2D Model test device.

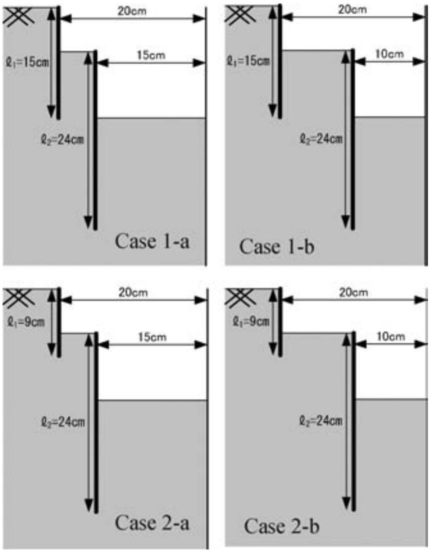


Figure 3. Cases of study.

Table 1. Material Parameters.

Ground	Aluminum rods Unit weight $\gamma = 20.4$ (kN/m^3)
Retain wall	Aluminum plate EI $= 0.88$ (kN*m^2/cm) EA $= 4.22 \times 10^4$ (kN/cm)
Strut	Upper: $k_l = 3.64$ (kN/m/cm) Lower: $k_l = 4.13$ (kN/m/cm)

Table 2. Parameters of ground made of aluminum rod mass.

λ	0.008	
κ	0.004	
$N - e_{NC}$ at $p - 98$ kPa & $q = 0$ kPa	0.3	same parameters as Cam-clay model
$R_{cs} = (\sigma_1/\sigma_3)cs$	1.8	
ν_e	0.2	
β	1.2	shape of yield surface (same as original Cam-clay at $\beta = 1$)
a	1300	influence of density and confining pressure

Figure 2 shows the schematic diagram of the two-dimensional apparatus. The size of the model ground is 68 cm in width and 45 cm in height. Aluminum rods of 5 cm in length, having diameters of 1.6 mm and 3.0 mm and mixed in the ratio of 3:2 in weight, are used as the model ground (unit weight of the mass is 20.4 kN/m^3). In the experiment, the model ground was excavated with a thickness of 1.5 cm each time and two struts, located at the levels of −1.5 cm and −7.5 cm respectively, were set into place at the time when excavating level reached −1.5 cm below its position. The retaining walls, with different length and spacing, were set before the ground was excavated. Table 1 shows the material parameters of the model ground, the retaining wall (Aluminum plate) and the struts. A laser type displacement transducer is used to measure surface settlement of the ground. By taking photographs with a digital camera and using image processing of the photos, the distribution of movement and consequently the strain of the ground can be measured.

Numerical analyses are carried out with the same scale of the model test considering plane strain condition using isoparametric element. An elastoplastic constitutive model, named as subloading t_{ij} model (Nakai & Hinokio, 2004) is used in the finite element analyses to simulate the mechanical behaviors of the model ground. The model can take into consideration automatically the influence of the intermediate principal stress, by introducing a modified stress t_{ij} (Nakai and Mihara, 1984; Nakai and Matsuoka, 1986). Subloading surface concept proposed by Hashiguchi (1980) was also adopted in the model to consider the influence of density of ground materials. Detailed description about the performance and the reasoning of the model can be referred to aforementioned references.

Table 2 lists the parameters of model ground made of aluminum rod. Figure 4 shows the performance of the model. Figure 5 shows the finite element mesh of Case1-b. Smooth boundary condition is assumed for side boundaries, and the bottom of the meshes is kept fixed. The initial stresses of the ground are calculated by simulating the self-weight consolidation by applying body forces, starting from a negligible confining pressure ($p_0 = 9.8 \times 10^{-6}$ kPa) and an initial void ratio

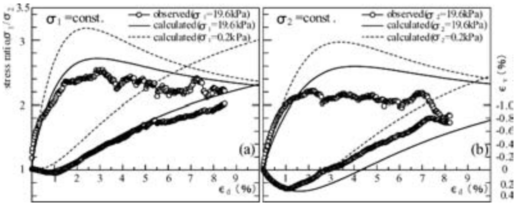


Figure 4. Stress-strain-dilatancy curves for aluminum rod mass.

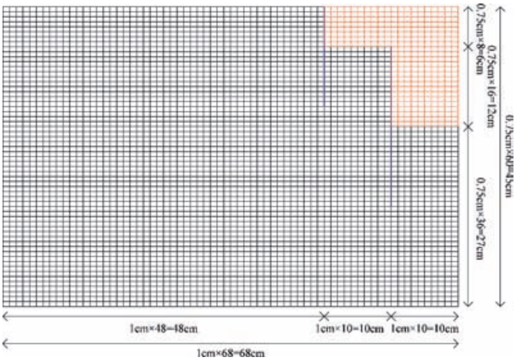


Figure 5. Finite element mesh (Case1-b).

e = 0.35. The retaining wall was simulated with beam element and the strut is simulated with spring element. Between the ground and the retaining wall, joint element whose mechanical behavior is simulated by a perfect-plastic joint elements (Nakai, 1985), was introduced to consider possible sliding between the ground and the wall.

3 RESULTS AND DISCUSSION

Figure 6 shows the observed surface settlements at different excavation stages in four cases. The length of outer retaining wall does not affect too much the settlement, while the spacing of twin walls has a great influence on the settlement. The shorter the spacing is, the larger the settlement will be. The same tendency can be obtained in the correspondent calculations, as shown in Figure 7.

Figures 8 and 9 show the observed and calculated deflections of the retaining walls during the excavation. Similar to the surface settlement, the main factor affecting the deflection is the spacing of twin walls.

From Figures 6 to 9, it is also known that the numerical calculation conducted in this paper can not only well describe the deformation patterns of the ground and the retaining wall qualitatively but also quantitatively to some extent.

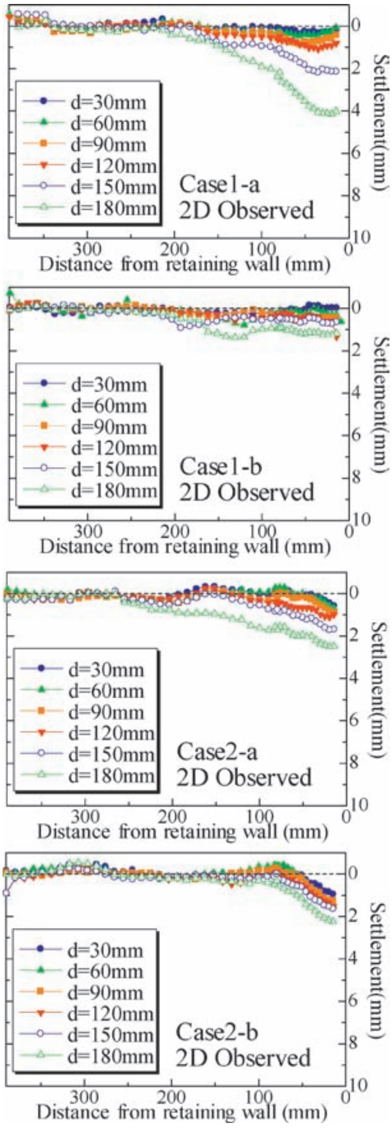


Figure 6. Surface settlements (Observed).

In the calculation, the frictional angle of joint elements which are used to simulate the friction between the ground and the wall is determined with constant normal stress frictional test and is found to be 17 degree. In the calculation, however, the displacement of the ground along the wall does not fit the observed one well. This is due to the fact that a perfect-plastic model is used for the joint elements which do not allow any elastic deformation before the joint element reaches yielding state. The reason why we do not use elasto-plastic model is that it is difficult to determine

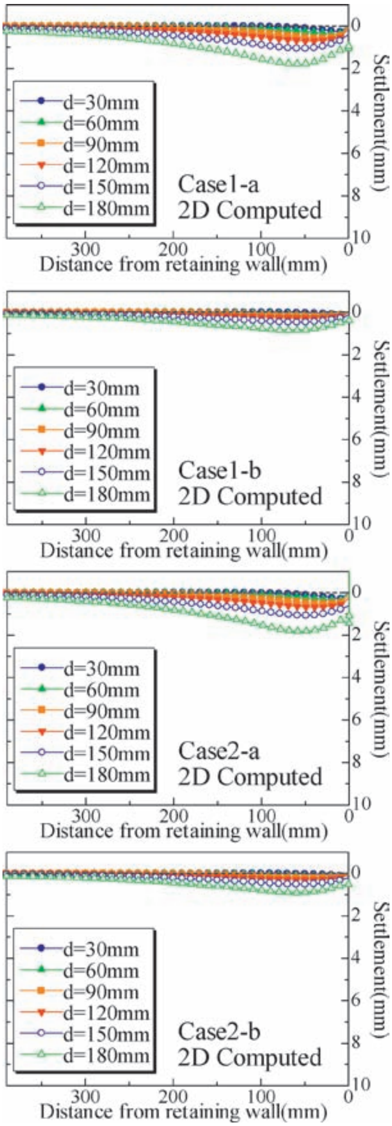


Figure 7. Surface settlements (Computed).

the shear stiffness of joint element. Further research needs to be down in future.

Figures 10 and 11 show the displacements of the ground surrounding the excavated area, obtained both from model test and numerical calculation. The deformation of the ground is limited to the area near the excavation. The calculated results agree well with the observed ones.

Figures 12 and 13 show the distribution of shear strain (The second invariant of strain tensor), obtained both from model test and numerical calculation. It is found that the shear strain of the ground is also limited

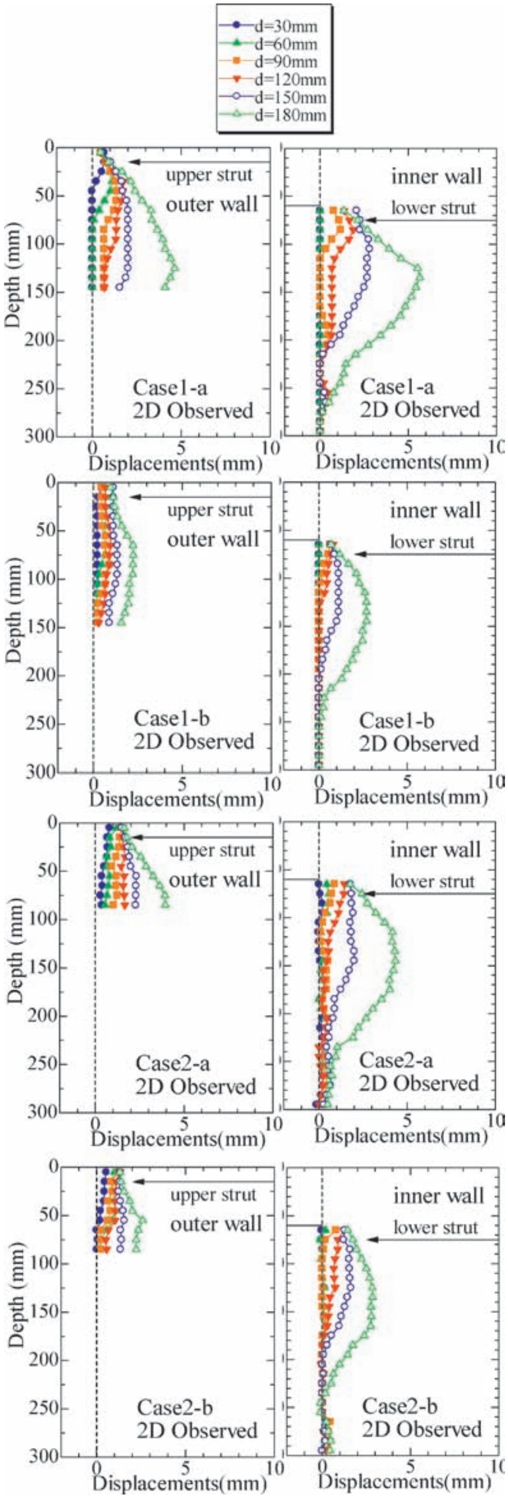


Figure 8. Displacements of retaining wall (Experiment).

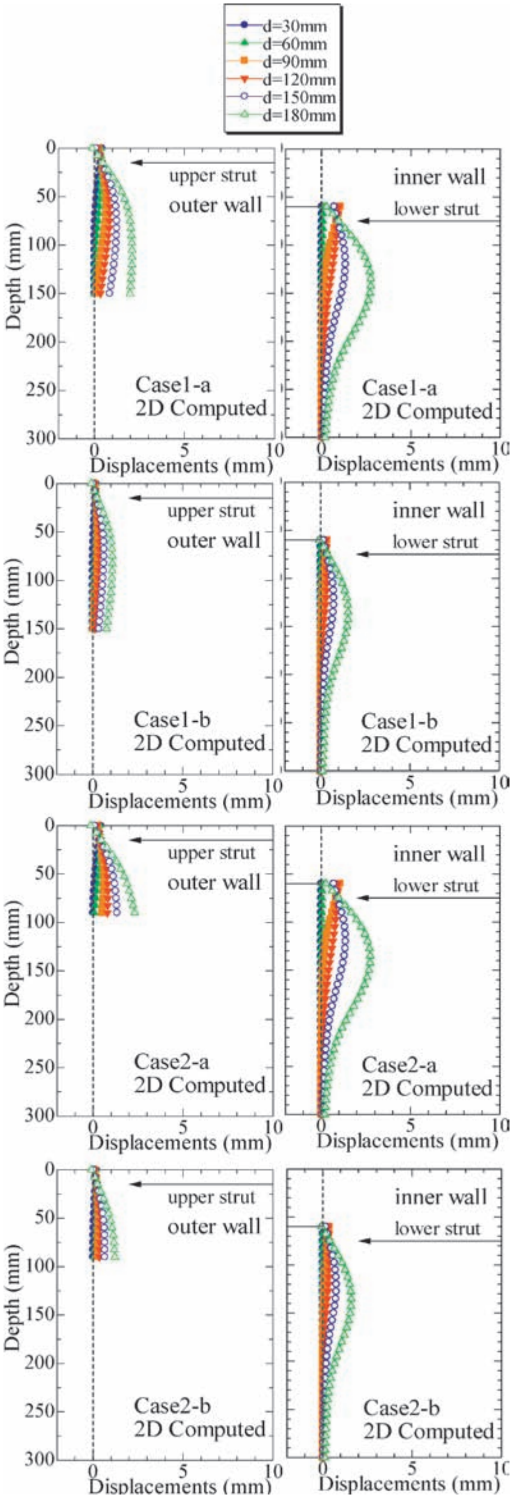


Figure 9. Displacements of retaining wall (Computed).

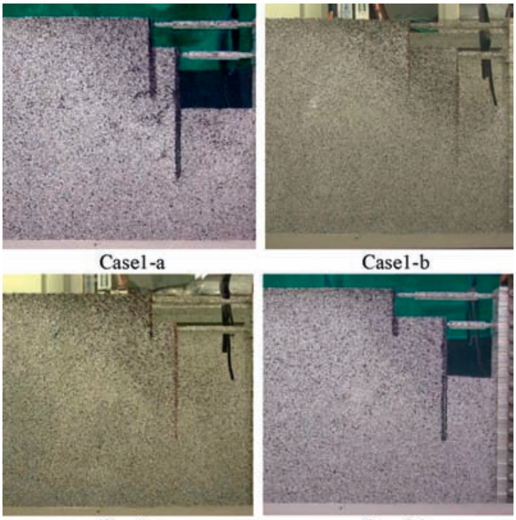


Figure 10. Displacement of ground (Observed, d = 180 mm).

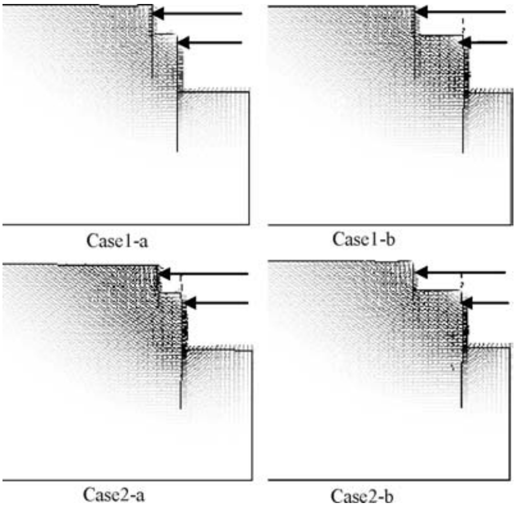


Figure 11. Displacement of ground (Computed, d = 180 mm).

to the area near the excavation. The calculated results agree well with the observed ones.

Figure 14 gives a comparison between the observed and the calculated results of axial forces within the struts at different excavating stages. Similar to the surface settlement, the main factor affecting the axial force is the spacing of twin walls instead of the length of the outer wall. The closer the spacing is, the higher the axial force of the second strut will be. The first

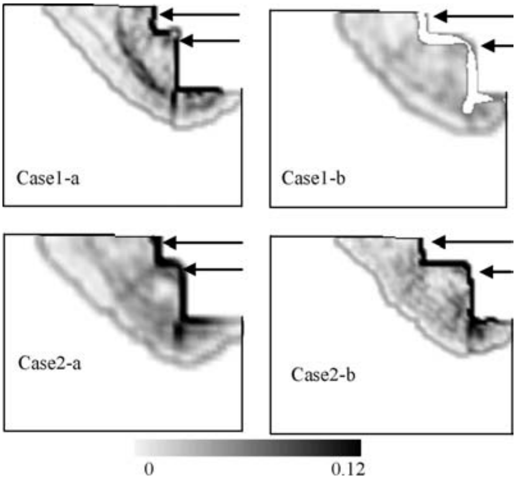


Figure 12. Distribution of shear strain (Observed, d = 180 mm).

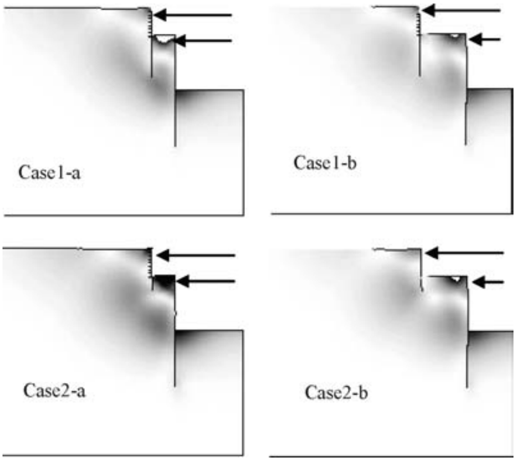


Figure 13. Distribution of shear strain (Computed, d = 180 mm).

strut, however, is not affected too much by these two factors, that is, the length of wall and the spacing. The numerical calculation can well describe the test results, both qualitatively and quantitatively.

Figure 15 gives a comparison of calculated change of earth pressures on retaining walls during excavation for the cases of 1-a and 1-b. It is found that the earth pressures on inner retaining wall do not show much evident difference. The outer wall, however, does behave quite differently, that is, the passive earth pressure on the bottom in case 1-a (narrow spacing) is much smaller than those in 1-b (wide spacing), implying that the ground between the twin wall cannot be expected to resist the deflection of the outer wall as what we usually expected to be a passive earth pressure when the spacing of the two wall is enough narrow.

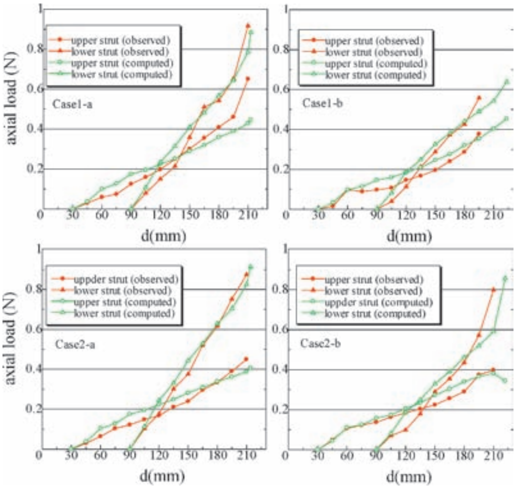


Figure 14. Comparison of axial forces in struts.

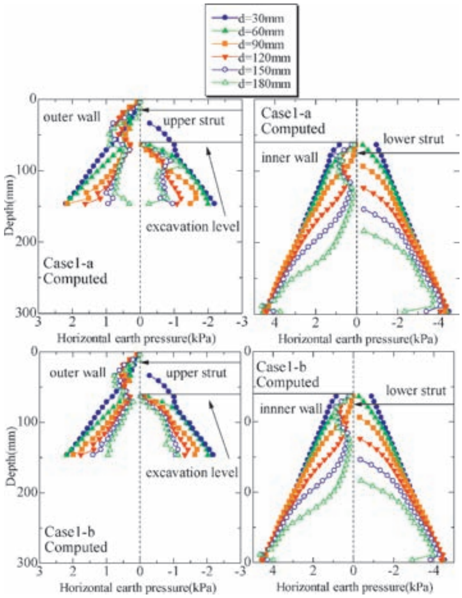
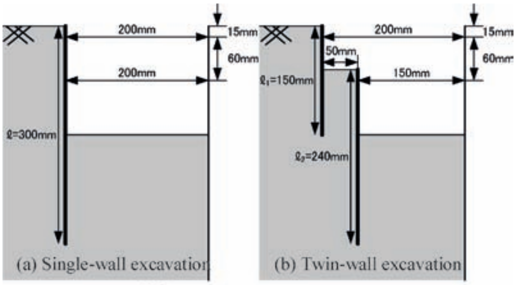
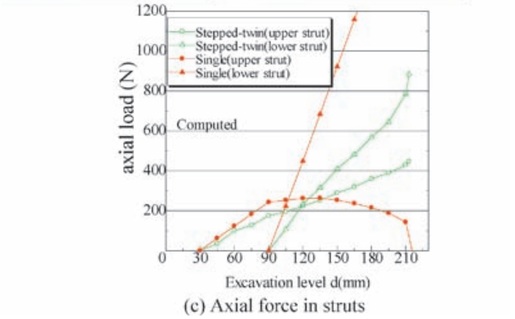


Figure 15. Change of earth pressures on retaining walls during excavation.

Figure 16 shows a comparison of calculated results of axial forces in struts in different excavation methods. In single-wall excavation, the axial force in upper strut increases firstly and then decreases after the lower strut comes into action. In twin-wall excavation, however, both the axial forces in upper and lower struts increase during the excavation. Meanwhile, the



(a) Single-wall excavation (b) Twin-wall excavation



(c) Axial force in struts

Figure 16. Comparison of different excavation methods.

axial force of lower strut increases much fast in twin-wall excavation than those in single-wall excavation. Therefore the mechanism of twin-wall excavation and single-wall excavation is much different and should be considered carefully in daily design.

4 CONCLUSIONS

Laboratory model tests and the corresponding numerical simulations are conducted for investigating the deformation mechanism of the ground and earth pressure of the stepped-twin retaining wall. From this research the following points can be concluded:

1. The displacements of the walls are inversely proportional to the distance between the walls.
2. The surface settlement follows the same tendency of the wall displacements, and it is very much dependent on the distance between the two walls.
3. The distance between the walls is more important factor than the embedded length of the wall.
4. Unlike the single retaining wall the struts of the stepped-twin retaining wall share axial load a more efficient way.

Finite element analysis conducted in this paper, which is based on subloading t_{ij} model and, is capable to describe the mechanical behaviors of the twin-wall excavation qualitatively and quantitatively.

REFERENCES

Hashiguchi, K. 1980. Constitutive equation of elastoplastic materials with elasto-plastic transition. *Jour. of Appli. Mech.* ASME 102(2): 266–272.

Nakai, T. 1985. Finite element computations for active and passive earth pressure problems of retaining problems. *Soils and Foundations* 25(3): 98–112.

Nakai, T. & Hinokio, M. 2004. A simple elastoplastic model for normally and over consolidated soils with unified material parameters. *Soils and Foundations* 44(2): 53–70.

Nakai, T. & Matsuoka, H. 1986. A generalized elastoplastic constitutive model for clay in three-dimensional stresses. *Soils and Foundations* 26(3): 81–98.

Nakai, T. & Mihara, Y. 1984. A new mechanical quantity for soils and its application to elastoplastic constitutive models. *Soils and Foundations* 24(2): 82–94.