The paper was published in the proceedings of the 10th European Conference on Numerical Methods in Geotechnical Engineering and was edited by Lidija Zdravkovic, Stavroula Kontoe, Aikaterini Tsiampousi and David Taborda. The conference was held from June 26th to June 28th 2023 at the Imperial College London, United Kingdom.

Proceedings 10th NUMGE 2023
10th European Conference on Numerical Methods in Geotechnical Engineering
Zdravkovic L, Kontoe S, Taborda DMG, Tsiampousi A (eds)

https://doi.org/10.53243/NUMGE2023-327

Numerical analysis of the behaviour of the sand sandwiched by two sheet piles

H. Sugimoto[1] , B. Chevalier[1] , P. Breul[1], T. Mukunoki [2], J. Otani[2]

[1] *Clermont-Auvergne INP, Institut Pascal, University of Clermont-Auvergne, Clermont-Ferrand, France*
[2]*Faculty of Advanced Science and Technology, Kumamoto University, Kumamoto, Japan*

ABSTRACT: To rationalize open-cut construction by eliminating or reducing the cut beams, the double sheet pile method with a fixed head was developed as new earth retaining method. To develop the design method and clarify the behaviour of the soil between two sheet piles (referred hereafter as 'inner soil'), a numerical model using the discrete element method (DEM) was developed to observe the behaviour of the sand sandwiched by two sheet piles. Firstly, the density and triaxial compression tests were conducted to model the general friction angle of sand. After that, using the parameters set which were calibrated by the triaxial test on DEM, a horizontal loading test was conducted with two sheet piles and the inner soil and compared with the experimental results. By these, it is confirmed that this model can reproduce the results of the experiment. Moreover, analysis of the stress state during loading reveals how the stress state of the inner soil changes. Developing this model allows us to consider the soil-structure interaction problem in this method from the aspect of numerical analysis and to think of various construction conditions for more rational design and construction.

Keywords: sheet pile, soil-structure interaction, discrete element method

1 INTRODUCTION

Sheet pile is used as the revetment, retaining wall, and temporary construction to prevent collapse or water intrusion. Conventional construction methods, particularly self-standing wall construction, have the advantage of being affected by process or site restrictions. However, it has the problem of construction costs. Therefore, the head-fixed double sheet pile method is being developed as a method that can reduce the deformation of earth retaining walls more than ever before while keeping construction costs down. Figure 1 shows the concept of this construction method. In this method, two sheet piles are constructed in parallel and the heads of each sheet pile are fixed to make the rigid framestructure. This method is expected to reduce deformation about six times more effectively than a single sheet pile. Increased deformation control is expected to reduce the number of cut beams and reduce construction site restrictions, and it is expected to greatly improve constructability. On the other hand, it has been found that in addition to the property of sheet piles, the property of the soil between two sheet piles (referred hereafter as 'inner soil') contributes significantly to the deformation control effect of this method. However, it is still unclear under what specific condition and mechanism of deformation control. A detailed assessment of inner soil behaviour and clarification of the reinforcement mechanism is one of the most important topics for establishing a design method to evaluate the effect of this construction method.

This paper focuses on the behaviour of inner soil and analyses the behaviour of this soil between two plates using the discrete element method (DEM) and finite difference method (FDM) coupling and compare it with experimental results carried out under similar conditions. Compared to the conventional double sheet pile method without head fixation, (e.g. Sawaguchi(1974), Fujiwara et al. (2017)) it is significantly important to consider the soil-structure interaction problem in this method, because of the narrow distance between two sheet piles and the large contact surface area between inner soil and sheet piles. On the other hand, the discrete element method can directly represent the contact between soil particles and structure, making it an easy approach to soil-structure interaction problems. The first part of this

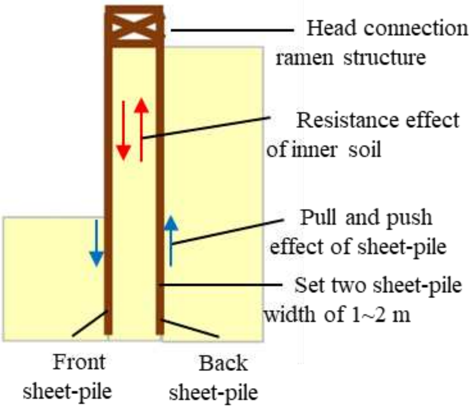

Figure.1 Overview of double sheet pile construction method

article deals with the numerical parameters calibration refered with Toyoura sand experimental parameters by using the inverse analysis of density and triaxial compression tests. Then a coupled FDM-DEM analysis was conducted where sheet piles are modeled by finite elements and the inner soil by discrete elements, to evaluate the behaviour of the entire structure during horizontal head loading. Based on these analyses, detailed findings regarding the behaviour of soils sandwiched between two plates are discussed by calculating the stress and displacement fields in the specimen, with comparisons to experimental results.

2 DISCRETE ELEMENT METHOD

The discrete element method is one of the numerical modelling method to analyze the behavior of the discontinuous body such as granular materials. Unlike continuum analysis, such as the finite element method, it is suitable for representing the dynamic and contact behaviour of aggregates. A simple contact model is introduced between the elements, and independent simultaneous equations are set up for each element, which are solved in a time-forward manner. Although a lot of models have been proposed for contact modelling, the rolling resistance linear model (Iwashita and Oda, 1998) which allows the particle shape to be considered as rotational friction, was adopted for the general linear model in this study. Moreover, Aboul et al. (2017) considered the behaviour of particles when rolling friction is introduced in the DEM and investigate how the various parameters of DEM affect the overall behaviour of the specimen. Normally, soil particles have a complex shape, which generates resistance to rotational moments, however, in the model proposed here, no resistance to moments occurs because spherical shaped particles are used. Therefore, rolling resistance is provided by defining friction concerning the rotational moment. Detailed equations and algorithms for rolling friction resistance contact model are mentioned in the following text (Itasca, (2019)).

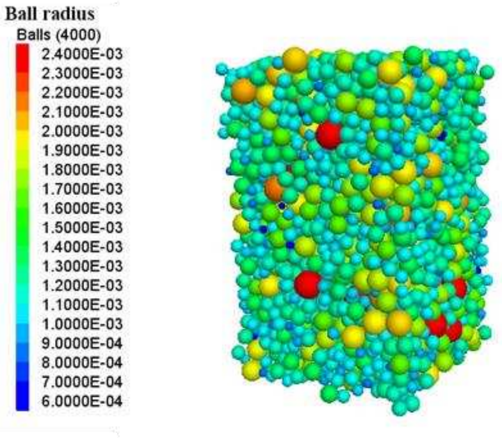

Figure.2 Three dimensional view of the triaxial compression test

The analyses in this study were carried out using PFC 6.0 and FLAC 6.0 developed by Itasca. The discrete element used in the analysis were modelled as a discontinuum using PFC6.0 and the sheet piles were modelled as a continuum using FLAC6.0 for the coupled DEM-FDM analysis.

3 DENSITY AND TRIAXIAL COMPRESSION TEST FOR CALIBLATION

3.1 *Numerical model of the density and triaxial compression test*

Firstly, to determine the parameters of the discrete element method, inverse analysis was conducted on the density and triaxial compression test. Figure 2 shows a three-dimensional view of the triaxial compression test. For specimen preparation, the isotropic compression method (Cundall and Strack,. 1979) and the particle expansion method (Jean et al., 2009) have been proposed, and in both methods, the initial relative density of the specimen can be adjusted by manipulating the friction coefficient. In this study, we finally used the isotropic compression method to make a specimen in DEM for the sake of optimizing the calculation time.The specimen was prepared with periodic boundary conditions, in an isotropic stress state by randomly generating 4000 discrete elements following the characterictics of the particle size distribution of Toyoura sand, which is the standard sand in Japan. For reasons of calculation time, the analysis was conducted using particles 12 times larger than the actual Toyoura sand grain size. Figure 3 shows the particle size distribution of Toyoura sand and DEM. After that, a 50 kPa confining pressure was applied to the specimen to compact it. At this phase, the density of the specimen was examined. Finally, the specimen was then loaded by applying velocities to the upper boundary while isostatic pressure was applied on the all specimen sides in horizontal direction. Table 1 shows the parameter set for the triaxial compression test on DEM. The kratio mean normal stiffness divided by shear stiffness, and damping ratio is the parameter for local damping. The size of specimen was 50mm long, 30mm wide, and 30mm thick after confining pressurewas applied. There were 20 particles across the smallest specimen dimension with this specimen and particle size. On the density test, the parameter set of Table 1 was used also and friction coefficient and rolling friction coefficient were changed only for parametric study.

3.2 Determine the parameter set for Toyoura sand

As a result on the density, Figure 4 shows the relationship between the friction coefficient and the porosity of the specimen after the confining pressure has been applied for different rolling friction coefficients. When the friction coefficient was 0.0, the porosity was around 0.33, indicating that a denser specimen than the actual porosity of Toyoura sand is produced, however, a looser specimen can be produced by increasing the friction coefficient.

Figure 5 shows the results of the friction angle fitting for the friction coefficient and rolling friction coefficient in the triaxial compression test with DEM. The calculated peak friction angle is 42 ° and the residual friction angle is 27 ° . For the peak friction angle, appropriate value were obtained, as mentioned in Fukushima et al (1984). However, the residual friction angle was lower than the real value for Toyoura sand. This is considered to be a problem caused by the difference in particle shape between the experimental and numerical analyses. It is presumed that this problem can be solved by using a geometry that simulates the original particle shape in the numerical analysis, however there is a problem that a large calculation cost is incurred. Therefore, in this study, the peak friction angle of the triaxial compression test was appropriately set in order to properly assess the peak strength of the horizontal loading test. Following horizontal loading tests were analyzed using this parameter set.

Table.1 Parameter list for the triaxial compression test

Emod(Pa)	2.5e7
Kratio = k_n/k_s	2.0
Damping ratio	0.5
Fric	0.65
Rolling fric	0.2
Number of particle	4000
Initial Dr(%)	90
Confine pressure(kPa)	50

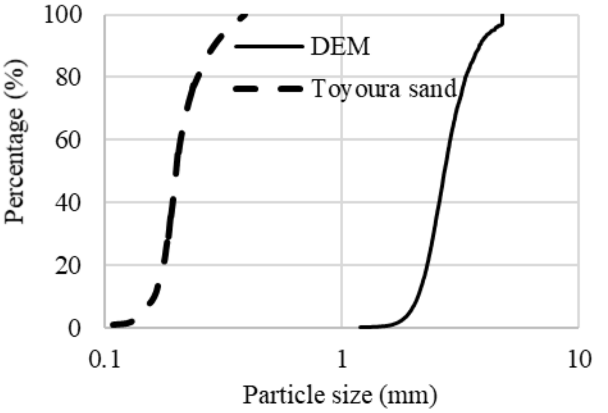

Figure.3 Particle size distribution on DEM referring with Toyoura sand

4 HORIZONTAL LOADING TEST

4.1 Modeling horizontal loading tests using FDM-DEM coupling analysis

Using the particle parameters obtained in section 3, horizontal loading tests were carried out on a specimen sandwiched between two shells using a coupled FDM-DEM. Figure 6 shows the three-dimensional view of a horizontal loading test. This test was conducted under application of a constant confining pressure. The specimen preparation and loading tests were carried out according to the following procedure:

i). The specimen was prepared using the isotropic compression method similar to triaxial

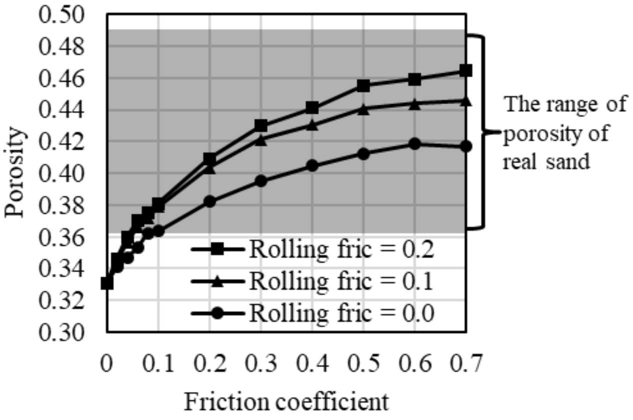

Figure.4 Results of parametric study of density test

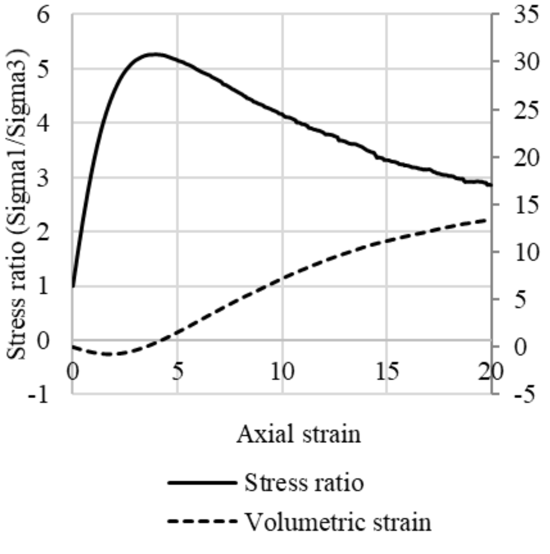

Figure.5 Stress ratio – axial strain relations and volumetric strain – axial strain relations for triaxial compression test with DEM

compression tests. In this case, no periodic boundary condition was applied.

ii). Two plates made of shell elements are placed on the sides of the specimen in the X direction. In the Y direction, plane wall are used to contain the material and apply a constant confining pressure.

iii). Apply to confine pressure to all surfaces and place the specimen under isostatic pressure.

iv). Extend the Shell elements at the top and bottom and use additional particle to manage the boundary conditions of shells: fixing the position at the bottom and apply a constant velocity in the X direction for loading phase. The green particle in figure 6 was for fixing the bottom of the shells (fixed in X, Y, and Z directions), the blue particles were for keeping the width of the sheet pile (fixed in X and Z directions) and the red particles were for loading (fixed in X and Z direction, applying on velocity in the Y direction).

v). Velocity was applied to the red particles and the horizontal displacement of the shell head and the load on it are measured. The load was measured by the summation of the contact force between the shell and the loading particles.

Table 2 summarized the parameters. The size of specimen and material parameter of sheet pile was refered by Sugimoto et al. (2022). In this experiment, 0.5 mm thick aluminium plates were placed on both sides of a 60 mm long, 60 mm wide and 160 mm high specimen, and horizontal loading tests were carried out under conditions of conceptual pressure applied by air pressure. In the present analysis, the specimen size and material constants were determined with reference to this experiment. Young's modulus value from the Japanese Industrial Standards (JIS) for aluminum plates of 1.0 mm thickness was applied in the numerical modelling. Each sheet pile is represented by 300 finite elements and can be deformed by horizontal loading.The rolling friction coefficient was not applied to the particle-plate contact, only the friction coefficient was given.

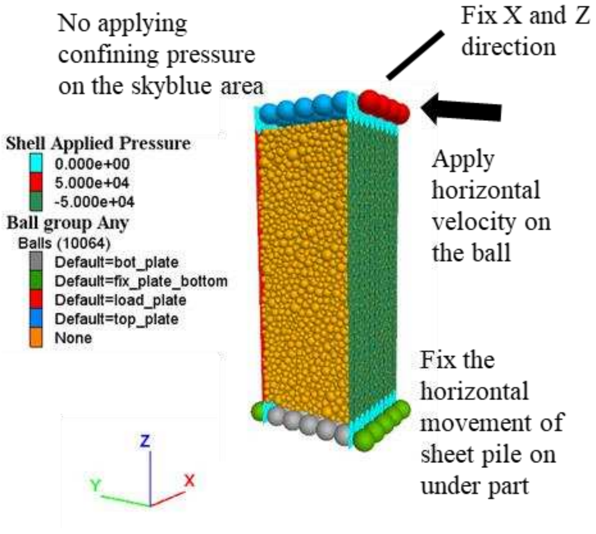

Figure.6 Three-dimensional view of the horizontal loading-test

4.2 Behaviour of sand between two shells

Figure 7 shows the results of the horizontal loading test in the numerical analysis as a relationship between the horizontal load and displacement of the specimen. As a comparison, the results of a horizontal loading test in an experiment conducted under the same condition as this numerical analysis are also shown (Sugimoto et al. 2022). In the experiment, the load increased linearly up to about 6 mm, from where the increase in load gradually converged and the final horizontal load was about 100 N. On the other hand, the numerical results showed a good representation of experimenta results. The experiments also showed a final horizontal load of approcimately 100 N. From these results, it was clear that the coupling of DEM and FDM can reproduce the results of horizontal loading tests under confining pressire conditions. When the number of particles is reduced (e.g., about 5000 particles), the mechanical behavior shows almost similar results. However, in the strain distribution analysis of the specimen, which is the goal of this

Table 2 Parameter list for the horizontal loading tests

Effective modulus(Pa)	2.5×10^7
Kratio = k_n/k_s	2.0
Damping ratio	0.5
Number of particle	10000
Number of element	2400
Ball fric	0.65
Ball rolling_fric	0.2
Ball-wall fric	0.05
Initial Dr(%)	80
Confine pressure(kPa)	50
Young's modulus (Sheet pile) (N/mm^2)	7×10^{10}
Poisson's ratio (Sheet pile)	0.3

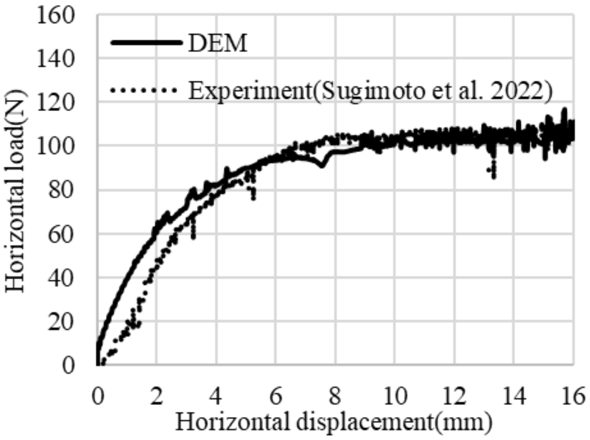

Figure.7 Load-displacement curve of horizontal loading test

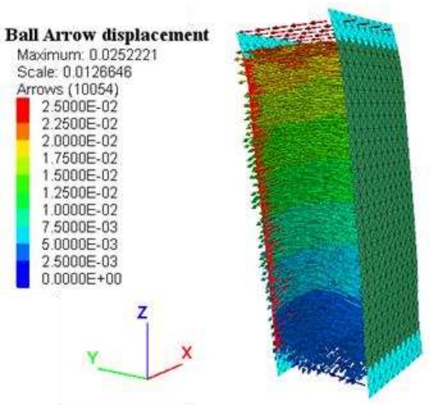

Figure.8 Displacement after 15mm horizontal loading with 50kPa confining pressure

study, it is expected that shear zones can be clearly expressed when the number of particles is increased.

Figure 8 shows the displacement field of each particle at 15 mm horizontal loading. It can be seen that the movement of each particle constituting the specimen generally behaves in the horizontal direction, however, the particles close to the right-side shell behave in the upper direction and those close to the left-side shell in the lower direction. On the other hand, the soil particles at the bottom of the specimen hardly move at all. Observation of the deformation mode of the entire specimen shows that the specimen behaves like a single beam. The two sheet piles behaved parallel and no bending-like behaviour was observed. This is considered to be due to the shell and soil particles becoming one rigid object and exerting horizontal bearing capacity.

Figure 9 shows the stress-shear strain curves inside the specimen in the X, Y, and Z directions during horizontal loading. The stresses were measured by calculating the average value of the stresses acting on the particles in the measurement sphere region located in the center of the specimen (Itasca., 2019). An isotropic pressure of 50 kPa was applied, therefore the pre-loading condition is the stress of 50 kPa inside the specimen in all directions. It can be seen that as the horizontal displacement increases, the stress in the Z-direction increase, while the stress in the Y-direction and X-direction decreases. As for the stress in the Z-direction, no change is observed up to about 5mm, after which it was found to increase rapidly. The decrease in stress in the X-direction and Y-direction and the increasing stress in the Z-direction indicate that the stress state in the specimen is gradually shifting to the active state. The deformation of the specimen reveals that the reinforcing effect of the inner soil is lost due to the gradual transition to the active stress state.

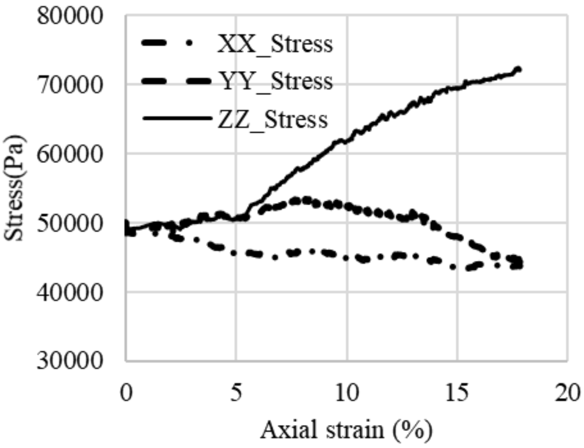

Figure.9 Stress- strain curve of horizontal loading test with 50kPa confining pressure

5 CONCLUSION

This study aimed to clarify the behaviour of the sand sandwiched by two plates to understand the reinforced mechanism of the double sheet pile construction method. For this purpose, firstly, each parameter of DEM for Toyoura sand was calibrated by the inverse analysis of density and triaxial compression test. After that, a coupled FDM-DEM analysis was conducted to clarify the behaviour of sand sandwiched by two shells. The finding of this study are summarized as follow:

1) The mechanical behaviour of general sand could be reproduced to some extent for the phase of low strain using the discrete element method.
2) The results of the analysis of horizontal loading tests on two plates and specimens using FDM-DEM coupling analysis showed a good representation of the experiements results. From the load-displacement curve, it was found that the load increased up to a certain amount of displacement, after which the horizontal bearing capacity remained constant without decreasing.
3) The specimen exhibited a single beam-like deformation behaviour during horizontal loading.

This suggests that the plate and soil particles become one rigid body and the structure is capable of providing horizontal bearing capacity.

4) It was found that the stress state in the specimen gradually shifts to the active stress state as the shear strain increases. It indicates that the stress state of the inner soil has a significant influence on the horizontal bearing capacity of the entire structure.

6 REFERENCE

Aboul Hosn, R., Sibille, L., Benahmed, N. and Chareyre, B., 2017. Discrete numerical modeling of loose soil with spherical particles and interparticle rolling friction. *Granular Matter*. **19**(4).

Cundall, P. A., Strack, O. D. L. 1979. A discrete numerical model for granular assemblies. *Géotechnique*, **29(1)**, 47–65.

Fujiwara, K., Taenaka, S., Otsushi, K., Yashima, A., Sawada, K., Hara, T., Ogawa, T., Takeda, K. 2017. Study on coastal levee reinforcement using double sheet-piles with partition walls. *International Mini Symposium Chubu*, **5**(2), 11–15.

Fukushima, S., Tatsuoka, F. 1984. Strength and deformation characteristics of saturated sand at extremely low pressures. Soils and Foundation, **24**, 30–48.

Itasca, 2019. Particle Flow Code 6.0 Documentation.

Iwashita K., Oda, M. 1998. Rolling resistance at contacts in simulation of shear band. *Journal of Engineering Mechanics*, **124**, 285–292.

Nasu, A., Kobayashi, T., Nagatani, H., Ohno, S., Inoue, N., Taira, Y., Sakanashi, T., Kikuchi, Y., 2021. Physical and numerical modeling of self-supporting retaining structure using double sheet pile walls. *Proceeding of Second International Conference Press-In Engineering 2021*, 330–336. CRC Press, United-states

Sawaguchi, M. 1974. Lateral behavior of a double sheet pile wall structure. *Soils and Foundations*, **14(1)**, 45-59

Sugimoto, H., Akagi, S., Sato, T., Jun, O., Nagatani, H., Nasu, A. 2021. Model test on double sheet-pile method for excavation works using X-ray CT. *Proceedings of the Second Internatinal Conference on Press-in Engineering 2021*.312-322. CRC Press, United-states

Sugimoto, H., Nasu, A., Nagatani, H., Sato, T., Otani, J., Evaluation of inner soil behavior in head-fixed double sheet pile method using X-ray CT. 2022. *Proceeding of Japan Society of Civil Engineers 2022 Annual Meeting,* III-18

Wensrich, C. M., Katterfeld, A. 2012. Rolling friction as a technique for modelling particle shape in DEM. *Powder Technology*, **217**, 409–417.