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NUMERICAL SIMULATION OF STAGED BRACED EXCAVATION IN SAND ~ O6 MRT STATION

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ABSTRACT: A numerical model for long-term drained analysis of staged excavation is developed and validated with a case history in this paper. Kaohsiung O6 station in Taiwan is selected for this purpose. A complete soil-structure interaction is considered in the current analysis which involves structural elements for diaphragm wall and strutting with preloading. *FISH* scripts are used to simulate staged strutted excavation using the finite difference program *FLAC*. Within the framework of drained analysis for excavation in the sand, dewatering is performed for each stage of the excavation work. Field monitoring data from other published sources are used to compare with the results produced by the numerical model. The main purpose of this paper is to demonstrate the usefulness of the development in assisting design and monitoring construction of deep braced excavation. The developed model can be used to assist future design and construction projects.

Keywords: FLAC, Drained analysis, KRTS, Deep braced excavation.

1. INTRODUCTION

Deep excavation, or the construction of basements, includes the construction of retaining walls (diaphragm wall), excavation, installation of struts and preloading, constructions of foundations and floor slabs. There are different types of excavation methods such as the full open cut method, the braced excavation method, and the anchored excavation method. The braced excavation method is the most common method being used in practice.

Due to rapid urban developments, many deep excavation projects for multi-story buildings and subways have recently been constructed. These construction projects may lead to the damage to adjacent structures because of ground movement. As well known, it is difficult to measure the ground movement and wall deformation during the construction process of deep excavation. This problem is faced in many projects during the stages of construction.

The use of computer-aided design methods to predict wall deflections and soil settlements has become popular [1]. In particular, the use of numerical modelings to simulate the behavior of geotechnical structures has increased dramatically over the years. There are different numerical techniques available including a finite element or finite difference method to solve the equilibrium equations governing the boundary value of problems. Many large-scale analysis programs such as *ABAQUS*, *FLAC*, *Geo-Studio*, and *PLAXIS*, in addition to less well-known codes, are used in geotechnical engineering research and practice [2]. In this research, the finite difference program, *FLAC* [3] is adopted to study the behavior of wall deformation and ground settlement during the stages of construction of deep excavation. In order to develop the numerical model, a set of data has to be chosen and made available. Kaohsiung Rapid Transport System (*KRTS*), O6 station project has been chosen as a case study for this purpose.

2. O6 STATION EXCAVATION (KRTS)

Construction of the Kaohsiung Rapid Transport System (*KRTS*) in Taiwan began in 2002. The project consisted of two lines, the Red Line and Orange Line. The total route length of the system is 42.8 km, including 37 stations, 28 of them underground. The deep braced excavation method was used to construct all of the underground stations. All stations are linked by a total of 28 twin-bored tunnels throughout the whole system. The Orange Line is located in the Lingya and Sinsing districts in Kaohsiung city with three underground stations, O6, O7, and O8. A deep braced excavation at the O6 station on the orange line has been selected for the case study.

3. DESIGN AND CONSTRUCTION

The braced excavation for cut and cover tunnels were used for the O6 station. The length and width of the excavation were 194 and 20.7 m, respectively. The maximum excavation depth was 19.6 m. The reinforced concrete diaphragm wall was constructed as a retaining structure with dimensions of 1m width and 36 m length.

The wall was braced by the steel struts with the help of walers and splays. W-shaped steel sections were selected as horizontal struts. The depth and width of the flanges of these struts varied from 350 to 414 mm and 350 to 405 mm, respectively. The thicknesses of the flanges were 19–28 mm and the web thicknesses were 12–18 mm. Double-W-shaped steel sections were used for the 3rd, 4th and 5th level struts to provide additional support. The horizontal spacing of the struts was approximately 4.5 m. The struts levels and their properties are illustrated in Table 1.

The excavation was kept open by a strutted system comprising of steel king posts (center posts), walers, and 5 levels of struts. An extensive monitoring system was installed including settlement marker, tilting observation devices and settlement markers on the adjacent buildings, and electrical piezometers inside the excavation area.

Table 1 Properties of the struts [4]

Strut number	Strut depth(m)	Cross-sectional area m²
1	2.5	173.9×10^{-4}
2	5.9	218.7×10^{-4}
3	9.1	590.8×10^{-4}
4	12.6	590.8×10^{-4}
5	16.1	590.8×10^{-4}

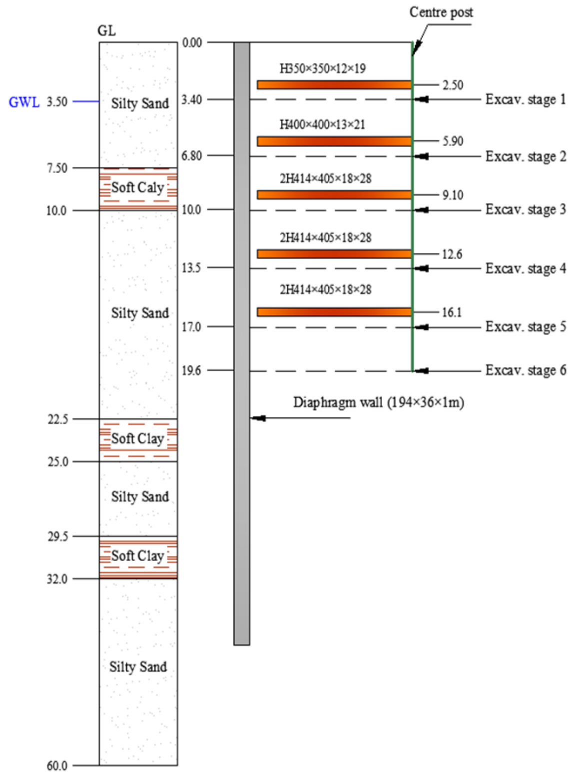

Fig 1 Cross-section of the excavation [4]

3.1 SOIL PROFILE AND PROPERTIES

As reported by [4], the soil layers were mainly silty sand and occasionally low plasticity silty clay deposits (Fig.1). Soil samples retrieved from the site were selected and tested in the laboratory. Testing programs included basic soil properties testing, direct shear tests, undrained and drained tri-axial tests, and oedometer tests. The effective friction angle measured from the direct shear tests and tri-axial consolidated undrained and drained tests performed on the soil samples was in the range of 32 to 33 degrees of sand and 30 to 33 degrees for clay. The unit weight of the soil varied from 18.6 to 19.9 kN/m³, and the *SPT-N* value varied from 5 to 42. A description of the ground profile and related soil parameters at O6 is given in Table 2. The cohesion of the silty sand was assumed to be zero. The groundwater level was observed at approximately 3.5 m below the surface.

Table 2 Soil profile and properties [4]

Soil type	Depth below GL m	Unit weight γ *(kN/m³)*	Friction angle ϕ
Yellow and grey silty sand	0.0-7.5	19.7	32
Grey silty clay with sandy silt	7.5-10.0	18.6	30
Grey silty sand, occasionally with sandy silt	10.0-22.5	19.6	32
Grey silty clay with silt	22.5-25.0	19.3	33
Grey silty sand with sandy silt	25.0-29.5	19.7	33
Grey silty clay	29.5-32.0	19.5	32
Grey silty sand with clay	32.0-60	19.9	33

3.2 NUMERICAL MODELLING

The analyses have been conducted by using effective stress formulation. The excavation is 20.7 m wide and the final depth is 19.6 m. The diaphragm walls extend to a 36 m depth and are braced by five horizontal struts levels. The initial water table is 3.5 m below the ground surface. The thickness of the diaphragm wall is 1.0 meter. The properties of struts are adopted from Table 1. The properties selected to simulate the behavior of the diaphragm wall are listed in Table 3. The Mohr-Coulomb soil properties chosen for analysis are adapted from Table 4. The soil elastic modulus, *E*, for each of the soil layers was calculated based on the relationship given by [4] as E = 2000N (kPa), where N is the average Standard Penetration Test value (*SPT-N*) of each soil layer as obtained from the site.

Table 3 Properties of diaphragm wall (*KRTS-O6*)

Width (m)	*ρ (kg/m³)*	*E (MPa)*	Poisson's ratio	*I* (m^4)
1.0	2400	19.2	0.2	0.08334

Table 4 Soil properties for modeling (*KRTS-O6*)

Soil type	*γ* kN/m³	*E* MPa	*c'* kN/m²	Friction angle *ϕ*
Yellow and grey silty sand	19.7	19	0	32
Grey silty clay with sandy silt	18.6	8	0	30
Grey silty sand, occasionally with sandy silt	19.6	28	0	32
Grey silty clay with silt	19.3	28	0	33
Grey silty sand with sandy silt	19.7	48	0	33
Grey silty clay	19.5	32	0	32
Grey silty sand with clay	19.9	70	0	33

3.3 Modelling procedure

The *FLAC* procedure to simulate the construction sequence of the deep braced excavation in O6 station is performed in ten steps:

1. Generate the model grid, and assign material models, material properties, and boundary conditions to represent the physical system
2. Initiate the state of the ground prior to construction
3. Determine the initial in-situ stress state of the ground with the diaphragm wall installed
4. Lower the water level within the region to be excavated to a depth of 19.8 meters below the ground surface
5. Excavate to a depth of 3.4 m
6. Install the horizontal struts at the wall, at a level of 2.50 m below ground surface
7. Obtaining results for Stage 1 (steps 5 and 6)
8. Excavate to a depth of 3.4 m, Second stage
9. Install the horizontal struts at the wall, at a level of 5.90 m below ground surface
10. Obtaining results for the Stage 2.

Steps 8 to 10 are repeated until the excavation of Stage six is completed. The model can be created using either the *FLAC*'s graphical interface or directly using the command-driven mode. In this paper, the command-driven mode was used to develop a standard script for future uses.

4. RESULTS

After the successful creation of the numerical model, the various results are examined and some of the key outcomes are presented using *FLAC* program output.

4.1 Wall displacement

The displacement of the diaphragm wall at each excavation stage is indicated by the plot of x-displacement of the wall structure versus wall depth in Fig. 4 for the no preloaded struts. These plots are table plots generated using the *FISH* function (*wall_disp.fis*). The x-displacement and the y-position of each node along the wall are stored in ten tables corresponding to each excavation stage. The maximum deformation is approximately 45 mm at 21 m depth below ground surface. The maximum deformation occurred at the sixth stage of the excavation.

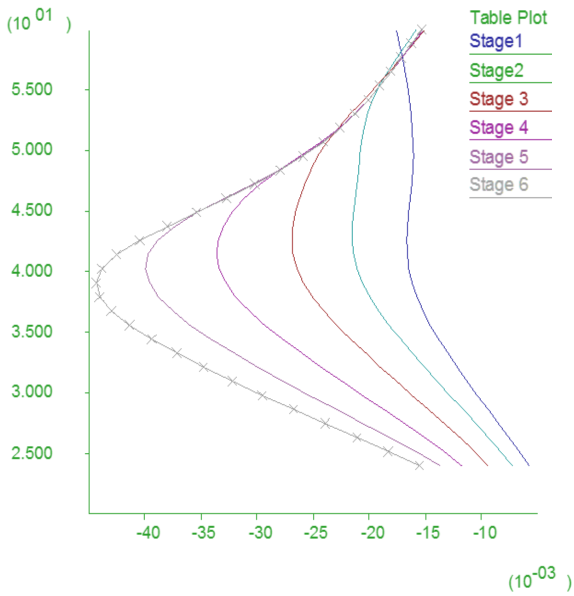

Fig.2 x-displacement of diaphragm wall (m) at each stage (x-disp versus depth)

4.2 Axial load in struts

The actual axial loads in the struts are calculated by the *FISH* functions using *strut_ax_load.fis* after the model has come to equilibrium for each excavation stage. The actual axial load values are then stored in tables for comparison at the end of the calculation.

As shown in Fig. 3, the axial load in strut 1 increases at the second stage, then decreases at the third and fourth stage and then increase slightly in the later stages. The axial load in strut 2 increases at the third stage then decreases at the fourth. All other strut load fluctuations are shown in Fig. 3.

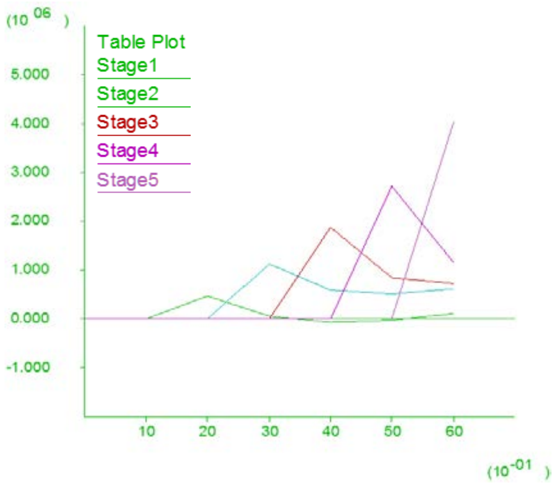

Fig.3 Axial forces (N) in struts at the end of each excavation stage (x-axis: stages 1-6)

4.3 Settlement

Settlements behind the diaphragm wall for the final stage of the excavation are plotted and shown in Fig. 4. The plot represents y-displacement of the soil versus horizontal distance from the diaphragm wall to 200 m. These plots are table plots generated using the *FISH* function (*settle.fis*). The maximum settlement is approximately 14 mm which occurs at 15 m behind the diaphragm wall.

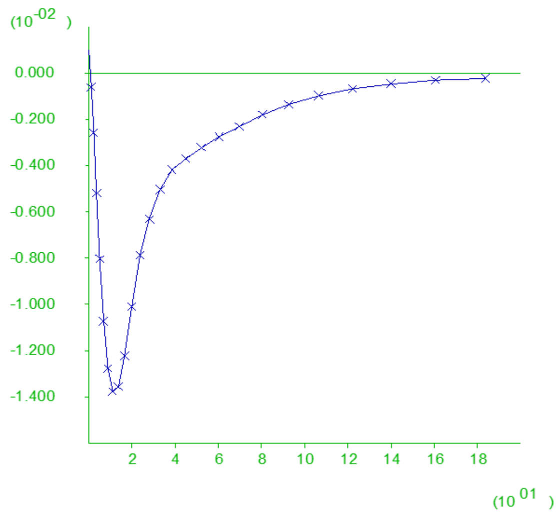

Fig.4 Surface settlement (m) profile final stage (x-axis: horizontal distance)

4.4 Bending Moment and Shear Force

Results for the bending moment and shear forces distribution are shown in Fig. 5 and Fig. 6 respectively.

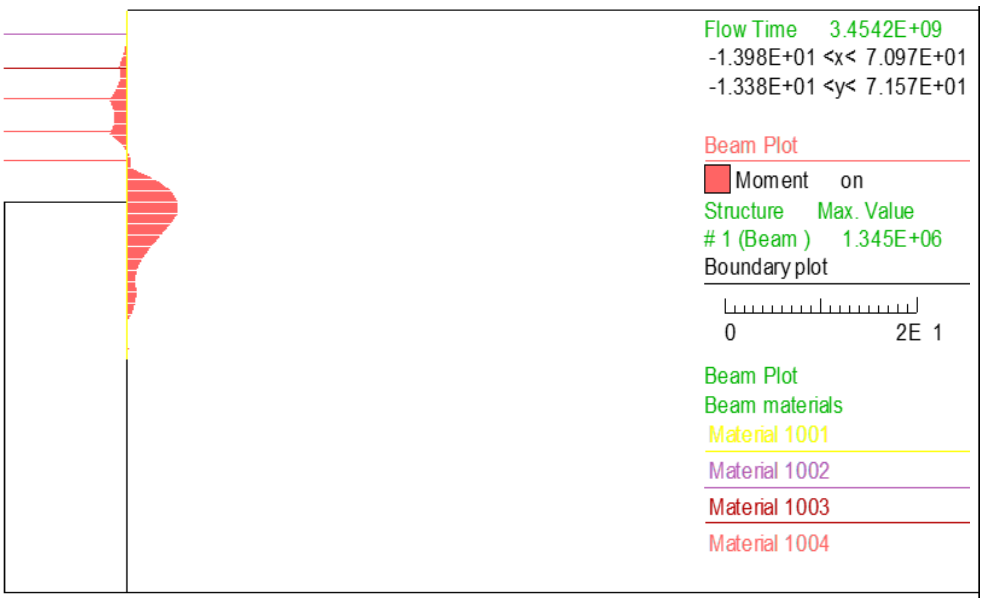

Fig.5 Moments (N-m) in the diaphragm wall at the final excavation stage

The maximum value of the moment is 1345 kN.m which is located in the middle of the wall while the maximum shear force is 540 kN. These values are recorded after the excavation of Stage 6.

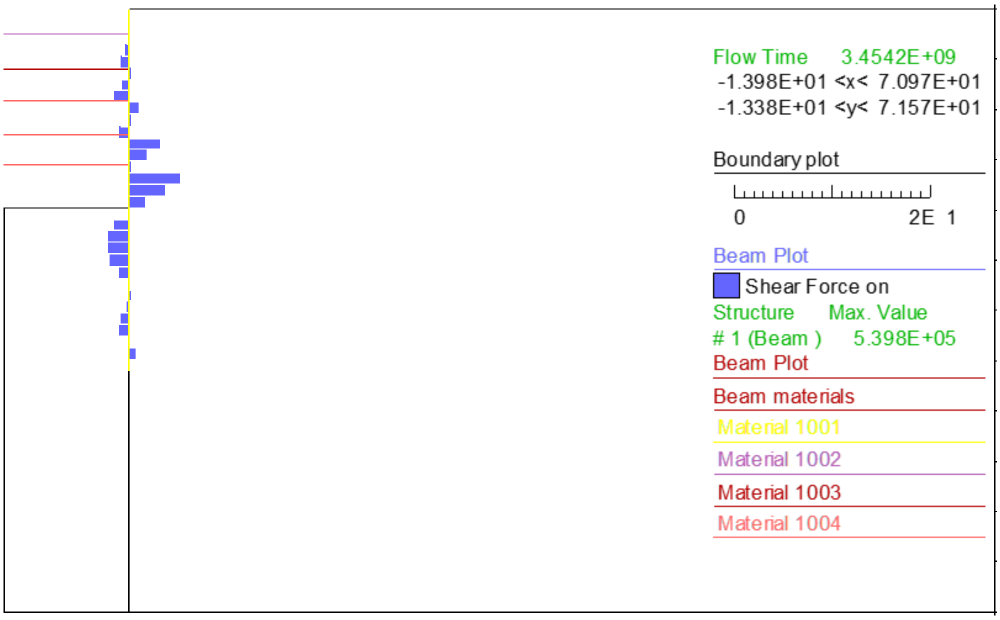

Fig.6 Shear forces (N) in the diaphragm wall at the final excavation stage

4.5 Y-Displacement Contour and Groundwater Table

Fig. 7 shows the plot of the Y-displacement contours and groundwater table after the final excavation stage. The maximum Y-displacement is recorded in the bottom of the excavation of final stage and the value is approximately 17 cm.

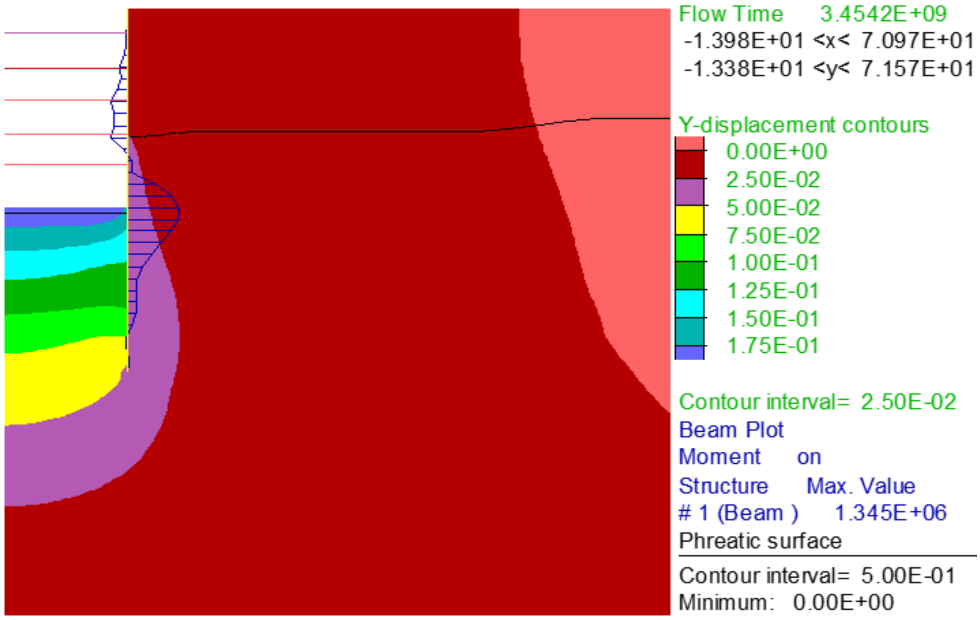

Fig.7 Y-displacement (m) at final excavation stage

4.6 Axial Force and x-Displacement Contour

Fig. 8 shows the plot of the X-displacement contours and axial forces in the struts after the final excavation stage.

The movements correspond to the increase in loads in the struts. Note that actual values for the axial forces are plotted directly for these plots. The maximum axial force is recorded in strut number six is 693 kN.

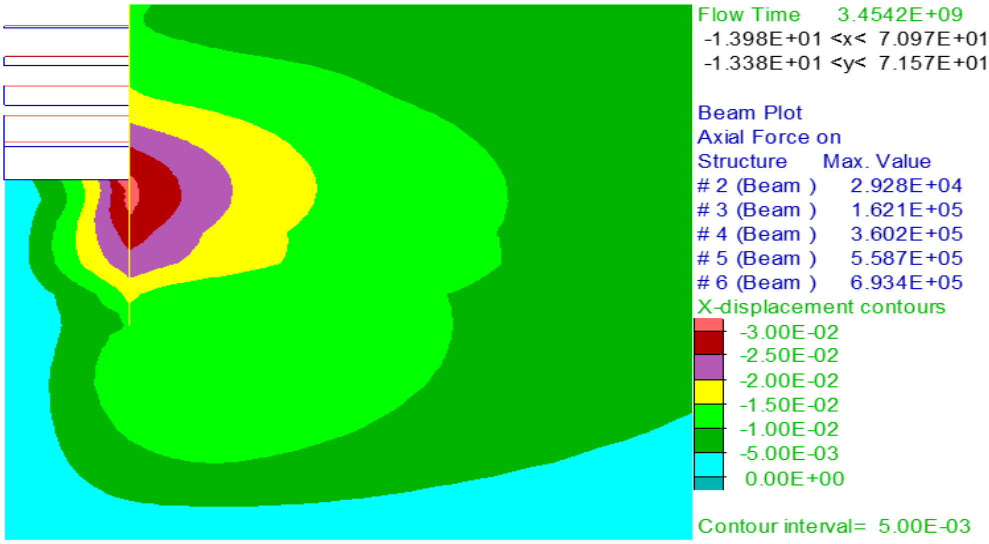

Fig.8 X-displacement contours (m) of the struts at the final excavation stage

5. COMPARISON

The computed values of wall deflection and ground settlement from this study are compared with the predicted values of wall deflection and filed measurement reported by [4] at Stage six of the excavation. This comparison is shown in Fig. 9 and Fig. 10. The comparisons are in reasonable agreement considering the uncertainties and complexities involved in the analysis. The values of wall deflection from the present study are more reasonable and close to the observed value.

The maximum value of wall deflection from the drained analysis based on this study was approximately 4.5 centimeters, which is very close to the observed value of the wall deflection, i.e. 5.2 cm. The maximum value of wall deflection as reported by [5] was approximately 6.2 centimeters.

6. INVESTIGATION AND DISCUSSION

According to the geology of the site work, most of the layers of soil were silty sand with the groundwater table is just below 3.5 m from the ground surface. As a result, the analyses were carried out for drained analysis for sand. In this case, there was no preloading on the struts. The values of wall deformation and lateral settlement were reasonable according to previous studies. Local experience has shown that lateral displacement of diaphragm walls resulting from basement excavation alone may reach up to 0.3–0.5% of the basement excavation depth under normal construction conditions [6]. Therefore, for the O6 excavation, a maximum lateral diaphragm wall displacement ranging from 4.5 to 7 cm was likely as a result of basement excavation. The predicted value of the ground settlement compared very well to the value reported by [6].

The ground settlement value depends on the excavation depth and lateral wall deflection. The magnitude of the excavation related ground surface settlement falls between 50 and 100% of the measured lateral maximum wall displacement [6]. In spite of this, it is known that in the numerical modeling using the *FLAC* program, the interface properties such as friction and cohesion have a direct effect on the ground settlement.

The maximum value of the y-displacement vector at the bottom of the excavation was approximately 20 cm which is a considerably large value. For uniform elastic properties, the linear elastic/perfectly plastic Mohr-Coulomb model may predict unrealistically large deformations in soils subjected to loading and unloading, such as heave induced at the bottom of excavations [6]. A more realistic calculation may be obtained by the nonlinear elastoplastic Cysoil model in the future.

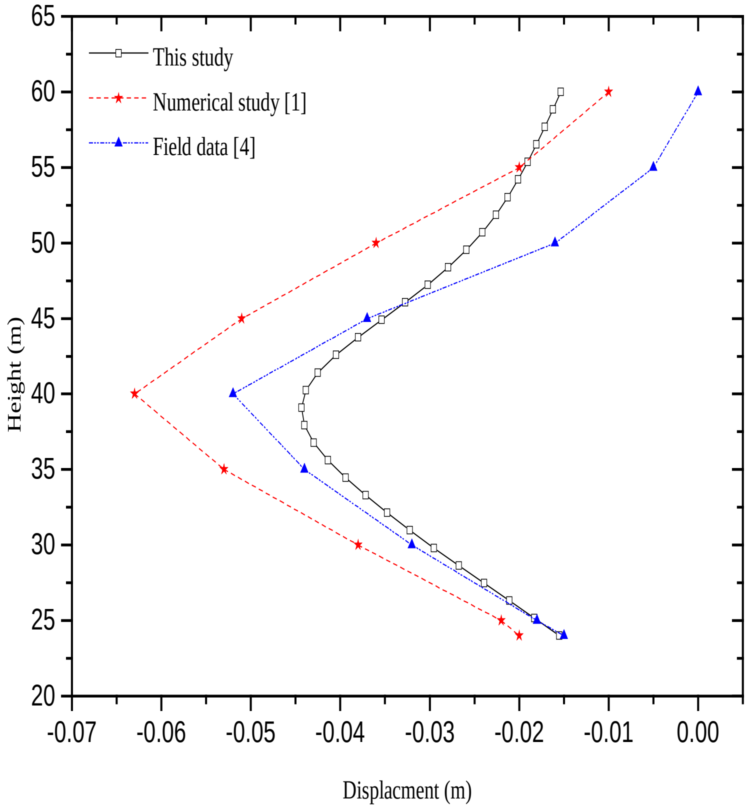

Fig.9 Comparison of wall deflection

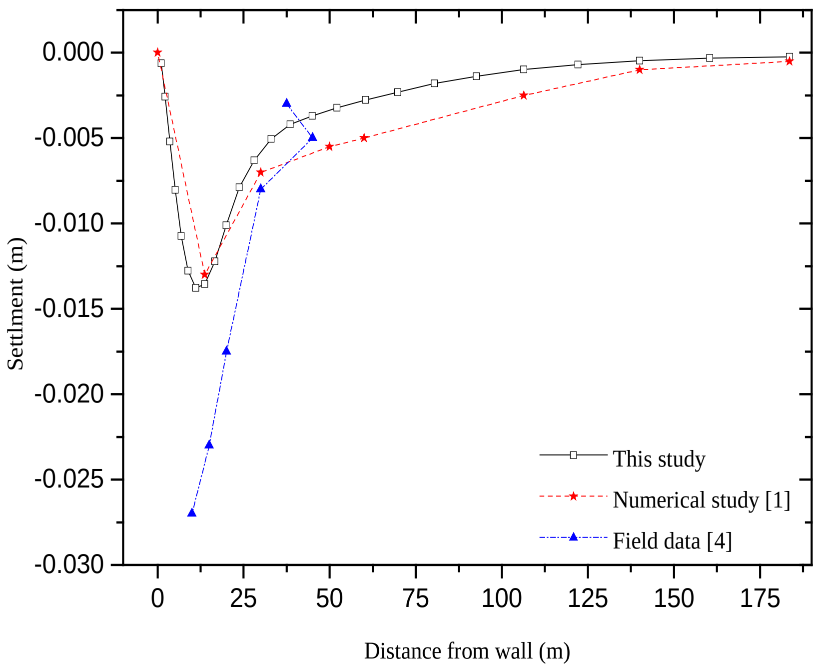

Fig.10 Comparison of ground settlement

7. CONCLUSIONS

A numerical model has been developed for staged braced excavation in long-term drained condition for sand. Kaohsiung O6 station excavation in Taiwan was used as the case study for this purpose. Within the drained analysis for excavation in the sand model, a none-preloaded strut was considered in the analyses for bracing the diaphragm wall.

The computed values of wall deflection and ground settlement from numerical modeling based on drained analyses from this study have been compared with the published results by [1] at stage six of the excavation. Considering the uncertainties and complexities involved in the analysis, the results have shown good agreement.

The results of this research reveal further study to be conducted. This may include the development of *3D* analysis model. Instead of using the Mohr-Coulomb model, the nonlinear elastoplastic Cysoil model could be used in the future study.

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