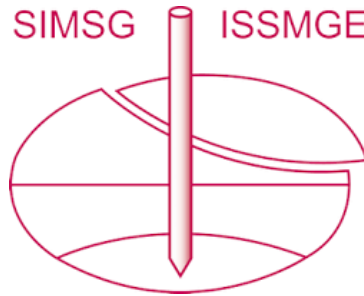


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Performances of deep braced excavation in anisotropic soft clay by different construction methods

Performances de l'excavation contreventée profonde dans l'argile molle anisotrope par différentes méthodes de construction

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ABSTRACT: Undisturbed clay shows significant differences in its mechanical properties under various stress states, the stress-strain relationship for different principal stress direction embodies significant anisotropy, which is defined as the stress-induced anisotropy. Reasonable and proper description of stress-induced anisotropy is essential in simulating complex geological conditions in the iterations of loading-unloading-reloading process, which is helpful in assessing the excavation safety and its impact on the surrounding environment. In present research, a series of 3D finite element analysis were conducted with reference to a practical underground subway station excavation in congested urban area. The NGI-ADP constitutive model was employed for simulating the clay stress-induced anisotropy. The performance of top-down and bottom-up construction methods was presented and compared in terms of wall deformation and ground movements. Accordingly, combined with the influence zones of deep excavation, the affected characteristics corresponding damage reduction measures of adjacent buildings were presented. So far, the responses and impact of excavation were thoroughly investigated for sake of excavation stability as well as the safety of the adjacent infrastructures.

RÉSUMÉ : Il existe des différences significatives dans les propriétés mécaniques des sols non perturbés dans différents états de contrainte, et les relations contrainte - déformation dans différentes directions de contrainte principale montrent une anisotropie évidente, c'est - à - dire une anisotropie induite par la contrainte. Une description raisonnable et appropriée de l'anisotropie des contraintes est essentielle pour simuler le processus de chargement et de déchargement répétés dans des conditions géologiques complexes, ce qui est utile pour évaluer la sécurité de l'excavation de la fosse de fondation et son influence sur l'environnement environnant. Dans cette étude, une série d'analyses tridimensionnelles par éléments finis ont été effectuées sur des projets d'excavation de stations souterraines dans des zones urbaines surpeuplées. Le modèle constitutif NGI - ADP a été utilisé pour simuler l'anisotropie induite par le stress de l'argile. La performance de deux méthodes de construction, descendante et ascendante, est introduite et comparée en termes de déformation du mur et de mouvement du sol. Par conséquent, les caractéristiques d'influence de l'excavation de la fosse de fondation sur les bâtiments adjacents et les mesures correspondantes de réduction des dommages sont proposées en combinaison avec la zone d'influence de l'excavation de la fosse de fondation profonde. Afin d'assurer la stabilité de la fosse de fondation et la sécurité de l'infrastructure adjacente, la réponse et l'influence de la fosse de fondation ont été étudiées en profondeur.

KEYWORDS: stress-induced anisotropy, braced excavation, Finite Element analysis, excavation response.

1 INTRODUCTION

Deep excavation is a crucial phase in the construction of superstructures and underground transportation system. In congested urban area, construction of braced excavation needs to ensure not only the stability of excavation itself, but also the integrity and serviceability of surrounding buildings (Zhang et al. 2018, Zhang et al. 2020, Zheng et al. 2018, 2020). The effects of braced excavation under various construction conditions on adjacent buildings have been studied by specialties in both time and space scale (Shi et al. 2015, Zhang et al. 2019, Zhou et al. 2020). Hsieh and Ou (1998) once partitioned the area behind the wall into the primary influence zone and secondary influence zone. The deformation characteristics of buildings located in different zones show great distinction (Schuster Kung). Based on the above achievements, in the designing phase, the adjacent building structure should be in the secondary influence zone, if possible, the further unaffected area.

Reasonable construction method and process is the premise to ensure the safety of braced excavation. According to specific requirements of different projects, engineers generally choose either the bottom-up (BU) or the top-down (TD) method to construct the foundation pit excavation. The top-down construction possesses the preponderance of stronger propping system through adopting several levels of underground structures to support the retaining wall. Furthermore, vertical support system is generally employed for the stability of underground structures, steel columns encased in concrete and steel tubes

erected in bored piles are widely constructed in this situation (Weng et al. 2016, Kung 2009, Zheng et al. 2020). While bottom-up method shows significant advantage of shorter excavation duration, reducing the soil exposure time. The retaining system required in bottom-up method is much succinct, where only wall and props are needed (Cheng et al. 2021, Tan et al. 2017). Kung compared the diaphragm wall deformation resulted from TD and BU excavations. It is concluded that according to whether observed data or analysis results, although the TD method adopts higher rigidity supporting components (basement floor slabs), it often leads to larger deformation.

For deep excavations in soft soils, the matters of poor design and the consequent large deformation problem still exist due to the incomprehensible understanding of the soils' natural mechanical properties (Zhang et al. 2020). The soil's complex characteristics, i.e., anisotropy, greatly manipulate its behavior (Zhuang and Cui 2016, Zhuang et al. 2020). The mechanical properties (i.e., strength and stiffness) of clay is significantly dependent on the principal stress direction, which is dominated by the loading/unloading process induced during excavation. This characteristic is called stress-induced anisotropy. The prominent impact of clay anisotropy on geotechnical constructions was confirmed in previous excavation analyses (Hanson and Clough 1981, Hsieh and Ou 2008, Keawsawasvong and Ukirchon 2021, Kong et al. 2012). For capturing soil anisotropic behavior, worldwide specialties have focused on the theoretical framework of critical state soil mechanics to establish clay anisotropic constitutive models, e.g., SANICLAY model

(Dafalias et al. 2006, Rezania et al. 2016) and bounding surface-based models (Cheng et al. 2020, Jiang et al. 2017). The present study quantifies the clay anisotropic degree using an advanced constitutive model NGI-ADP. The constitutive model is presented by the Norwegian Geotechnical Institute (NGI) and cored with the ADP concept (Bjerrum 1973).

This paper focuses on the environmental impact of deep braced excavation in strength and stiffness anisotropic soil. Firstly, three-dimensional FE model was established based on a well-documented excavation project in congested urban area, in which the NGI-ADP constitutive model was employed for simulating the clay stress-induced anisotropy. Comparison and discussion were made to reveal the different excavation responses caused by top-down and bottom-up construction methods. On this basis, the affected characteristics corresponding damage reduction measures of adjacent buildings were presented, aiming at providing guidance for the prevention and mitigation of environmental impact of deep excavation in dense building environment.

2 NUMERICAL MODELLING OF EXCAVATION CASE

2.1 Case history

This study reviewed a practical project, the excavation of Sukhumvit Station. It is a Bangkok Mass Rapid Transit Underground Railway station, located in a dense building environment. Surrounding infrastructures include 10 low rise buildings (3–4 storeys) and 1 tall building as shown in Figure 1. Geometries of the excavation is 200m in length and 23m in width, and the maximum excavation depth reaches GL-20.9m, according to the plan view of the excavation site. The field monitoring system consists of 8 inclinometers and a series of surface settlement array, whose locations are marked in Figure 1.

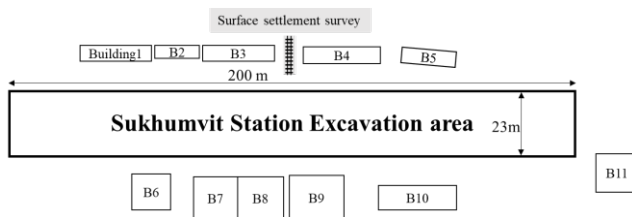


Figure 1 Excavation geometry and surrounding buildings

The subsoil distribution and sectional view of the excavation project are shown in Figure 2. Geological conditions of the excavation site can be simplified as alternating horizontal layers of sand and clay, with an overlying made ground layer. The clay layers cover dominant volumes behind the retaining wall. The top-down method was employed to construct the underground station. The construction sequences included multiple staged excavation and structural member installation.

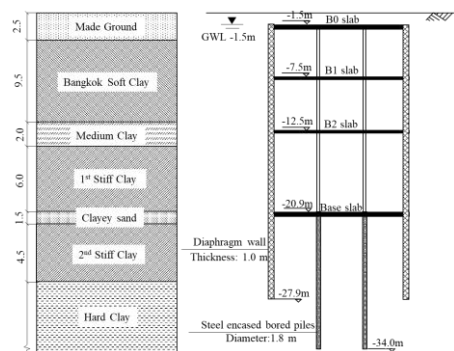


Figure 2. Site soil and underground structure layout

2.2 Numerical model

2.2.1 Model Geometry

Three-dimensional model was established centered with the station pit and surrounding buildings using the Finite Element software Plaxis3D. The vertical boundaries were extended far from the excavation to minimize the boundary restraints. The horizontal movement along the vertical boundaries were restrained while both the horizontal and vertical movements at the bottom were restrained. The details of the groundwater drawdown measure of the project remain unclear according to related reports. Therefore, it is assumed that before each excavation step, the groundwater level was dewatered below the excavation surface, and the outside groundwater level remained constant.

2.2.2 Site soil simulation

With reference to the Likitlersuang et al. (2013), the Hardening Soil (HS) model, proposed by Schanz et al (1999), was used to model the stress-strain responses of made ground and clayey sand. The HS model possesses three predefined stiffness parameters. They are E_{50}^{ref} , E_{oed}^{ref} , E_{ur}^{ref} which represent the reference secant stiffness from drained triaxial tests, tangential stiffness from oedometer primary loading, and loading-unloading stiffness, respectively. As for the clay layers (Bangkok soft clay, medium clay, first and second layer stiff clay, hard clay), the advanced anisotropic model NGI-ADP was employed to represent clay behavior. It is an anisotropic shear strength model where a nonlinear stress path-dependent hardening relationship is adopted. The employed yield criterion is based on a translated approximated Tresca criterion. As for its formulation, the clay stress paths under active (A), direct simple shear (DSS) and passive (P) loadings are distinguished. The anisotropic stress-strain relation under three different loading modes are derived from the results of triaxial compression (TXC), direct simple shear (DSS) and triaxial extension (TXE) tests. Six independent parameters from the three different stress paths, including undrained shear strengths s_u^A , s_u^{DSS} , s_u^P , and failure strains for triaxial compression γ^C , direct simple shear γ^{DSS} and triaxial extension γ^E , are defined as input to represent the strength and stiffness anisotropy. The model uses elliptical interpolation for plastic failure strains and shear strengths in arbitrary stress paths according to the above mentioned six parameters. The model using the ratio of different undrained shear strength indices to represent the soil anisotropic degree, i.e. s_u^P/s_u^A stands for the ratio of passive shear strength over active shear strength, ranging from 0 to 1, value of 1 represents the ideal isotropic condition. And G_u/s_u^A represents the ratio of undrained shear modulus over the active shear strength. The soil properties and corresponding values according to two different constitutive models are listed in Table 1.

Table 1. Soil model and parameter used for numerical analyses

Soil type	γ (kN/m ³)	Hardening Soil		
		c (kPa)	ϕ (°)	E_{50}^{ref} (MPa)
Made Ground	18	1	25	45.6
Clayey sand	19	1	27	38
NGI-ADP				
		s_u^A (kPa)	s_u^P/s_u^A	G_u/s_u^A
Bangkok soft clay	16.5	36.5	0.5	192
Medium clay	17.5	71.5	0.5	269
1 st stiff clay	19.5	105.6	0.5	400
1 st stiff clay	20	147.3	0.5	400
Hard clay	20	182.9	0.5	400

2.2.3 Retaining structures simulation

The earth retaining structural materials were idealized to be linear elastic. Their geometries are shown in Figure 2. The

mechanical properties can be found in Surarak et al. (2012). Additionally, the zero-thickness interfaces between the structures and soil were created to simulate the structure-soil interaction. The strength reduction factor of 0.9 for interface is assigned, characterizing the interface properties (including both strength and stiffness) according to a reduction rate of adjacent soil parameters in this study. Figure 3 shows the FE model for the Sukhumvit excavation. The simulation of buildings is composed of structural elements (plate, beam and pile) and uniform loads. Only 10 ground structures were built in the numerical model since the Building-11 locates at the corner of the excavation, the construction impact on B11 is negligible according to field data.

The conventional top-down construction sequence was adopted to simulate the actual construction process. After casting bored piles and inserting diaphragm walls, alternate excavation and construction of basement slabs were carried out, including implementation of installing and removing of two layers of temporary props.

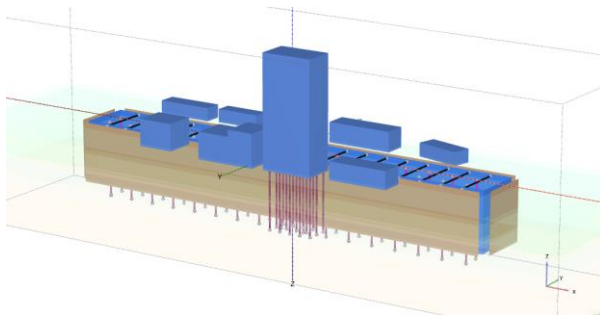


Figure 3. Structural members in FE model

2.3 Model validation

The accuracy of the numerical model is verified by comparing with the measured ground settlement. It can be seen that the computed trend of ground subsidence is consistent with the actual situation in the certain range (due to the limited monitoring area). The performance of anisotropic soil model can more satisfactorily predict the excavation response in contrast with the common isotropic hypothesis, which indicates that the NGI-ADP anisotropic model is conducive to capture the clay behavior encountered with the complex excavation situation. Subsequent parametric analysis adopting this model and relevant parameter can be conducted to solve the excavation environmental impact problem.

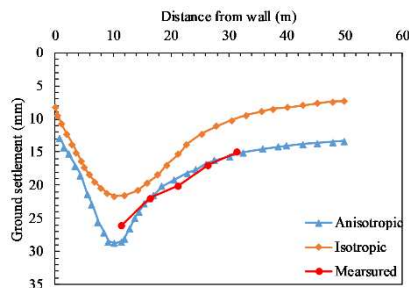


Figure 4. Computed ground settlement profiles with reference to measured data

3 PERFORMANCES OF CONSTRUCTION METHODS

At present, the construction of deep braced excavation is often carried out in the way of top-down or bottom-up method. In view of diverse engineering characteristics, the two excavation methods show different advantages and demerits. The support

system of top-down method shows higher capacities while the bottom-up method is propitious to save construction time.

For the above excavation case, the construction sequence of the two methods is shown in Figure 5 for comparison. It is obvious that the top-down method adopts the internal support system with better rigidity, including four levels of underground floor and two levels of temporary steel props. When simulating the BU method, the time interval of propping stage is greatly reduced to improve its performance.

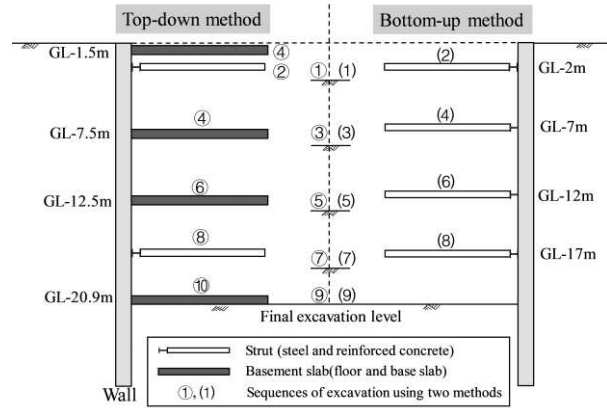


Figure 5 Construction sequences of two methods

3.1 Comparison of wall deflections

3.1.1 Maximum wall deflection values

Firstly, the qualitative influence of clay anisotropy degree on excavation response is briefly discussed. Four arithmetic s_u^P/s_u^A values were determined from 0.4 to 1 since it is reported that the s_u^P/s_u^A generally falls within the range 0.5 - 0.7 for natural clay (Grimstad et al. 2012, Panagoulas et al. 2018, Ukritchon and Booyatee 2015).

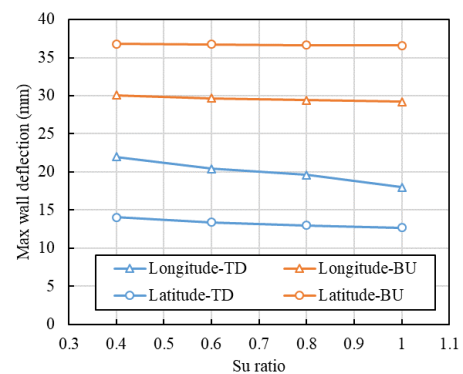


Figure 6. Maximum wall deflections for different s_u ratios

The variation of the maximum deformation values of both longitude and latitude diaphragm walls is shown in Figure 6. Longitude refers to the long side of the wall, while latitude refers to the other vertical direction. It can be known that TD braced excavation induced wall deflection maintains at a low level in both longitude and latitude direction. And due the corner effect, the deformation in the longitudinal direction is larger. However, for the BU completed excavation where diaphragm walls are only restrained by the transverse props, the maximum wall deflection values are significantly severer, especially in the latitudinal direction. It may result from the inconvenience of installing wholesale props to resist the inner movement. As for the effect of anisotropic degree, in general, it has no obvious impact on the wall lateral movements.

3.1.2 Wall deflection profiles

In addition, the critical wall deflection profiles of both longitudinal and latitudinal directions under the two excavation methods are compared under the typical anisotropic condition, i.e. $s_u^P/s_u^A=0.6$. Significant differences in deformation pattern can be observed from Figure 7. The typical concave wall deflection profiles were formed in the process of the bottom-up construction. Due to the horizontal and vertical spacing between props, the propping system stiffness is relative weaker, resulting in the smooth wall deformation profiles. It is worth noting that the maximum lateral displacement caused in BU construction is not near the final excavation level (FEL), but at the depth of 7-10 m. This is because the FEL is located in the stiff clay layer, and the large deformation is mainly manipulated by the weak Bangkok soft clay, which is lying at the depth of 2.5-12m. In contrast, the wall deflection profiles in TD method is obviously controlled by the basement slabs. The overall deformation was greatly reduced, and the deformation value at the slab depths greatly slumped. More specifically, the maximum wall deflection occurs in the middle of slab levels

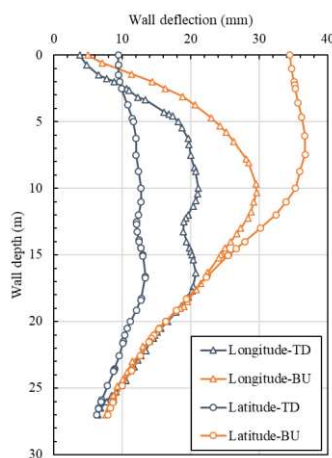


Figure 7. Wall deflections profiles under two construction methods

3.2 Comparison of ground movements

3.2.1 Displacement of soil behind wall

The influence of buildings around the excavation is closely related to the soil displacement field. For excavation conducted in the clay with anisotropic strength and stiffness, its stress and displacement situation shall be much different from the isotropic condition. Figure 8 displays the displacement vectors of soil outside the excavation area as a result of top-down construction.

The main differences between the two subfigures lie in the near surface position, which results from the stress-induced anisotropy. According to the three distinctive stress-strain relationships under different stress paths in Figure 9 (Panagoulas et al. 2018), its strength and stiffness suffer varying degrees of decay, resulting in more plastic elements and larger displacements.

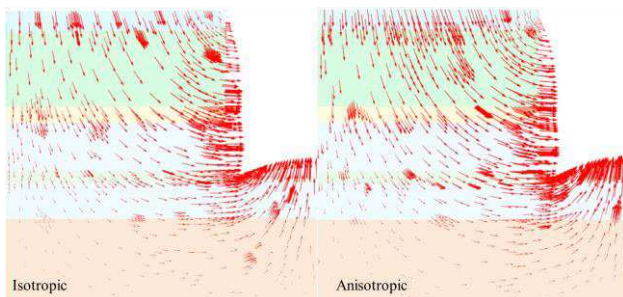


Figure 8. Effect of anisotropy on ground movements

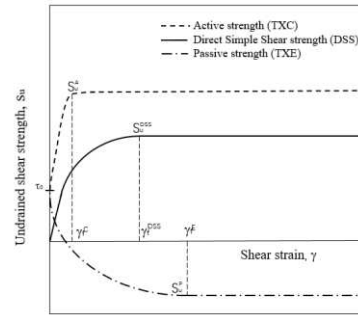


Figure 9. Stress-strain relations for three stress paths in NGI-ADP model

As for the comparison of BU and TD construction, firstly, the displacement of the soil right behind the retaining wall is similar to the wall deflection profiles, which is concave form of BU verses the deformation form of TD restrained by the structural slabs. The TD method shows great capability to reduce the basal heave as Figure 10 shows with the timely installation of base slab. Generally speaking, because the soil layer at the FEL and deeper layer are respectively stiff and hard clay with preferable properties, it is not likely to engender continuous sliding surface, which endangers the basal heave stability. What should be paid attention to is that the retaining wall constructed by the BU method may produce large deformation under the lateral thrust of Bangkok soft clay, which may further lead to local cracking and groundwater leakage problem.

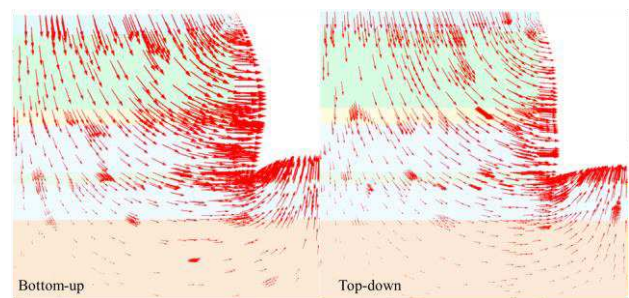


Figure 10. Displacement vectors of anisotropic soil behind the walls

3.2.2 Ground settlement

In the analysis of deep excavation environmental impact, ground settlement is an important index to evaluate its severity. In Figure 11, green field ground settlement profiles with consideration of both BU and TD construction methods are shown. And the ground settlement with the existence of adjacent buildings, more specifically, in the cross section at B9 is presented for comparison.

Similar to the above-mentioned results, the top-down method can better control the excavation responses, whether for retaining structure or surrounding soil. In addition, it can be seen that the ground settlement in dense building environment consists of subsidence induced by excavation and that caused by the loads from the ground structures. The settlement profiles suffer sharp increase at the location of existed ground buildings. It is revealed that when evaluating the excavation impact on surrounding building environment, the existence of buildings must be taken into account during the calculation.

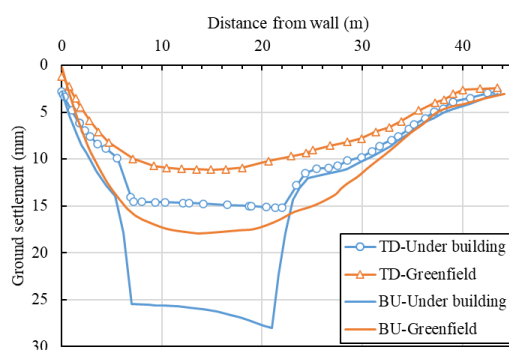


Figure 11. Ground settlement profiles using two construction methods

4 IMPACT ON ADJACENT BUILDINGS

4.1 Influence zone partition

The excavation impact on ground buildings is closely interfered with ground settlements at the certain location. In Figure 12, the ground settlement profiles are normalized and compared with the empirical curve proposed by published researches (Hsieh and Ou 2008). Results in present study is roughly consistent in trend with the previous research, where the maximum settlement occurs at the location $0.5H_e$ from the excavation side. With the distance increasing, the settlement decreases to a relatively low level when reaches two times of excavation depth distance. The difference in the descending part of settlement profiles may result from the existence of multi-layer heterogeneous soil and the thick Bangkok soft clay.

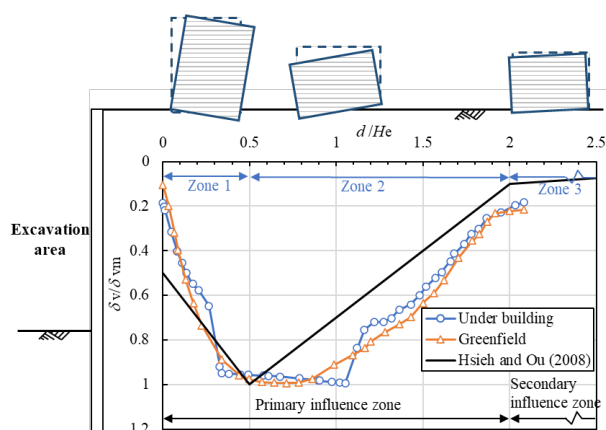


Figure 12 Division of influence zone and corresponding structure inclination

Based on the soil displacement severity, combining with Rankine theory, Hsieh and Ou (2008) identified this range as the primary influence zone of braced excavation, and the distance of $2H_e$ to $4H_e$ range as the secondary influence zone. Figure 11 also shows the inclination conditions of ground buildings lie in different areas. For structures located in the primary influence zone, large angular distortion may be induced, both serious sagging and hogging damages (Kung et al. 2007, Schuster et al. 2009) can be encountered. While for buildings erected in the secondary influence zone, they are less affected by the excavation complex excavation loading-reloading process. Based on Hsieh and Ou (1998) classification, this study divides the soil behind the wall into three zones for a clearer explanation, as shown by the blue sign in Figure 12.

4.2 Building responses

Further analysis was carried out for evaluating the effect of

braced excavation on adjacent infrastructures located in different influence zones with different foundation types. It is assumed that in the central section of excavation longitudinal direction, two buildings with strip foundation and pile foundation are distributed separately on two sides of the excavation. The burial depth of shallow foundation is 1m, and the pile reaches GL-24m, which is embedded in the stiff clay.

The building displacements in the three areas as shown in Figure 12 are listed in Table 2. Because the overall settlement is very small, the inclination of buildings is maintained minimal, with the emphasis on the inclination direction of buildings in different areas. It is labelled with the sign of inclination degree, the positive represents inclination towards the excavation, the minus indicates the building is leaning away from the excavation. It can be seen from the calculation results that only the shallow foundation building just near the diaphragm wall shows tilt against the excavation area, which is consistent with the ground settlement profile. The building with pile foundation at the same location shows the trend to incline towards the excavation under the manipulation of deep soil lateral movements.

Table 2. Building responses for TD construction method

Construction method		BU			TD		
Building zone		1	2	3	1	2	3
Strip-founded	Max settlement (mm)	17.6	25.6	10.3	8.4	12.1	8.3
	Inclination degree (‰)	0.7	1.2	0.3	-0.2	0.4	0.2
Pile-founded	Max settlement (mm)	10.7	11.7	7.9	6.8	9.5	5.8
	Inclination degree (‰)	0.3	0.3	0.2	0.2	0.1	0.2

The magnitude of displacements shows that the displacement of ground infrastructure does not hinge on the distance from excavation, but the distance from the potential sliding surface. However, it is not recommended that the building exists very close to the excavation edge, because the self weight and service loads of buildings in zone 1 increase the probability of basal heave failure, seriously endanger the stability of braced excavation (Goh et al. 2019). The ground subsidence of zone 2 decays rapidly with distance, buildings with wide span in this area may suffer uneven settlement damage. In this situation, pile foundation shows excellent performance without the influence upper soil. Building far away, i.e., in zone 3, was little affected by the excavation and retaining procedures due to the minor difference between BU and TD construction responses in Table 2.

Generally speaking, the influence on surrounding buildings caused by TD construction is smaller than BU in all zones. Buildings located in zone 1 worsen the excavation stability, buildings in zone 2 are in more critical state, and buildings beyond $2H_e$ distance from the excavation are marginally affected.

5 CONCLUSIONS

This paper presents the three-dimensional finite element analyses to assess the ground responses and adjacent building displacement for excavations in anisotropic soft clays. Main findings are as follows:

(1) The clay characteristic of anisotropy directly affects the soil displacement field, further influences the responses of adjacent buildings. The soil and buildings are subjected to much

severer deformation in anisotropic clay in contrast with isotropic condition.

(2) By adopting retaining system with higher rigidity, the top-down construction method can change the stress profiles along the retaining wall, as well as greatly reduce the displacement of site soil and adjacent buildings caused by excavation.

(3) The ground is divided into three zones according to different settlement features. The impact modes and suggested structural forms of infrastructures in different zones are presented.

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