Behaviours and mechanism analysis of deep excavation in sand caused by one-strut failure

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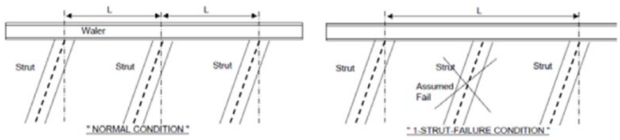
ABSTRACT

The strut failure is recognized as an important factor leading to overall failure of the deep excavation and said concern has been included in some countries of the world as a design requirement, it thus intends to explore behaviours and mechanism of a deep excavation in sand caused by one-strut failure (OSF). In order to conduct analyses stated above, finite element analyses with three-dimensional modeling are adopted and cases with removal of a single strut at various locations and depths at selected excavation stages are simulated. Behaviours and mechanism under said circumstance are explored and discussed and attention are paid into change of effective horizontal stresses of soil mass and strut loads. Although this study presents the OSF case in sandy soil only, load transfer mechanism and influence zone outcomes after an occurrence of one failed strut are similar with excavations in clayey soil but a detailed exploration is deserved for further studies and discussions.

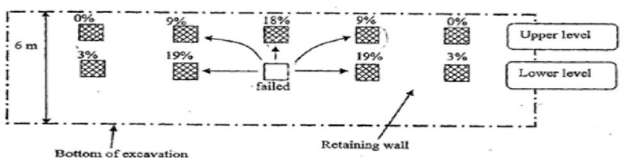
Keywords: deep excavation in sand; three- dimensional modeling; behaviors and mechanism for one-strut failure; 3D-2D conversion.

1. INTRODUCTION

A catastrophic disaster caused by the collapse of 33.3 m deep excavation in Singapore on April 2004 and it is concluded that failure of the 9th level strut is a key reason to initiate the collapse (Whittle and Davis, 2006). Puller (2003) also described overall failure of the excavation is likely to occur as a result of inadequate strutting. One-strut failure (OSF) design is thus introduced in Singapore and Malaysia after occurrence of the accident stated above for deep excavation. It is assumed that when any one strut, anchor or tieback at any one location is failed, temporary retaining earth structure (TRES) is still stable and additional load from the failed strut, anchor or tieback can still be safely undertaken by the rest (Suthiwarapirak, 2009 and TR26, 2010), as shown in Figure 1.



(a) Normal/one- strut failure condition



(b) Load distribution in OSF Case

Figure 1 Schematic drawing of OSF case

Due to the use of said design rule, some issues are therefore raised here because of (1) every deep excavation in general has more than one-level strut and each level again has more than one strut so which level strut at where shall be chosen as "failed" strut; (2) analyses for OSF is actually a three-dimensional (3D) problem and carrying out such 3D analyses is very time and cost-consuming. It is thus commonly seen that only 2-dimensional (2D) plane strain analyses are adopted and OSF case analysis involves removing an entire level of the deepest struts where loads are transferred to the remaining strut levels via the TRES walls. By doing so, designing for OSF becomes very conservative which does not fulfill the reality and also the purpose of sustainable development. For this reason, Pong et al. (2012) indicated the factor of reducing axial stiffness of strut instead of removing a whole strut level for the case OSF equal to 1.5 if 2D modelling is applied. Goh et al. (2017) thus further evaluate percentage of load transferring from the failed strut with various wall stiffness and it is likely an impact on strut load is comparatively insignificant for OSF case than expectation. It further states that the one-strut failure analysis involves an interaction process between neighbouring struts, between struts and wall and is affected by the strut location system stiffness, soil types etc. In this paper, the behaviour and mechanism of deep excavation after one strut failure are explored by investigation the changes in stresses and distributed strut loads. It is also aware the ground in this study is different with previous studies completed by Pong et al. (2012) and Goh et al. (2017).

2. RESEARCH BACKGROUND

2.1 Details of the excavation

An excavation in Kaohsiung in southern Taiwan is selected for this study. As indicated by Hsiung et al. (2016), a 16.8 m deep pit is retained by 0.9 m thick, 32 m deep diaphragm wall. The bottom-up method was carried out to construct the excavation through 5 excavation stages with 4 levels of steel struts. The ground condition basically includes a highly permeable thick layer of sandy soil and two thin clayey layers. Thus, the deep excavation is generally considered to fully rest on the loose to medium dense sand and the groundwater level is found at 2 m below the surface level.

2.2 OSF cases

To examine possible impacts of deep excavation with occurrence of OSF, only six cases are selected first and details of each case, such as maximum excavation depth, number of strut level and depth of lowest strut are presented in Table 1. Depths of each strut level from the 1st to 4th level are the same with Hsiung et al. (2016) and the size of 5th to 9th level strut for Cases 2 to 6 remain the same with the 4th level strut. From Case 2 to Case 6, it excavates 3 m more for each case except Case 6 which is 2 m only. The wall length and thickness have to reach up to a certain level for each case to ensure that the excavation remains stable. Table 1 also shows interpreted safety factor against push-in failure.

Table 1. Summary of the 3D Finite-Element Analysis for OSF

Cases	Excavation Depth, H_e (m)	Number of strut level	Lowest strut level, (m)	FS (push-in)
1*	16.8	4	13	1.7
2	19.8	5	15.8	1.95
3	22.8	6	18.8	2.02
4	25.8	7	21.8	2.07
5	28.8	8	24.8	2.1
6	30.8	9	27.8	2.15

(*) *Details of the excavation are referred to Hsiung et al. (2016)*

3. NUMERICAL ANALYSES

3.1. Finite element analyses

The 3D finite element software named PLAXIS3D (version 2017), made by PLAXIS BV in Netherland was adopted to explore the mechanism of excavation induced by OSF at various depths and locations of the excavation. In order to elimate any impact from excavation activties on boundary of the model, the distance of mesh boundary in X and Y direction were ranged from 260 to 425 m and from 310 to 475 m, respectively for different cases due to various excavation depths. The distance from the excavation to the boundary has to remain at least seven times the maximum depth of excavation, H_e. For boundation in Z direction, it sets to 60 m below surface level based on the depth of deepest borehole data except Case 6. The depth of the boundary of Case 6 has to be extended until 70m due to extremely long wall rather than others. The type of mesh of "fine" is used for all analyses. The size of model and mesh for analyses are shown in Figure 3.

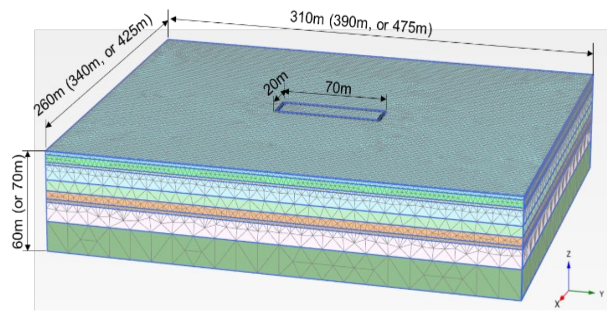


Fig. 3. Model and mesh of 3D Finite element analyses

3.2. Input parameters

An advanced constitutive soil model, Hardening Soil (HS) subjected to the unloading- reloading feature of soil was selected to perform soil behaviours induced by excavation in sand. In contrast, Mohr-Coulomb (MC) with "Urdrained B" analysis is chosen to define three clayey layers due to insignificant thickness and limits in having reliable input parameters (Hsiung et al, 2016). Plate element and node-to-node anchor element are used to simulate diaphragm wall and strut and parameters used are the same with Hsiung et al. (2016) too. The finite element mesh used in these models include averagely 645833 10-node quadratic tetrahedral elements with an average size is 4 m.

Table:2 HS soil input parameters for Sandy soils

Symbol	Unit	2	4	5	6	8	**9**
c'	kPa	0	0	0	0	0	0
ϕ'	°	32	32	32	33	34	34
E_{50}^{ref}	MPa	26.2	21.9	24.1	26.3	29.6	33.1
E_{oed}^{ref}	MPa	26.2	21.9	24.1	26.3	29.6	33.1
E_{ur}^{ref}	MPa	78.7	65.7	72.2	78.8	88.7	99.4
m	-	0.5	0.5	0.5	0.5	0.5	0.5
v'_{ur}	-	0.3	0.3	0.3	0.3	0.3	0.3
p^{ref}	kPa	100	100	100	100	100	100
R_{inter}	-	0.67	0.67	0.67	0.67	0.67	0.67

4. IMPACTS FROM OSF

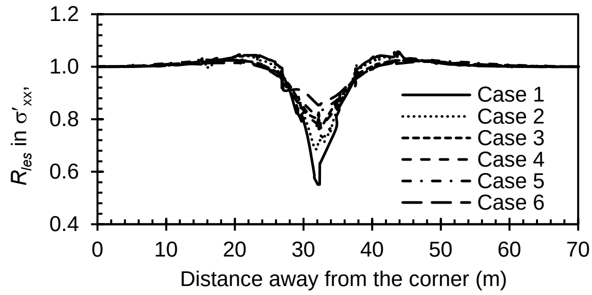
4.1 Soil stresses distribution

Impacts from OSF on lateral (horizontal) effective stress of soils in X (longitudinal) and Y (transverse) directions at various locations from the corner of the excavation are examined. An index so called "Ratio of lateral effective stress (R_{les})" is determined and used, as follows.

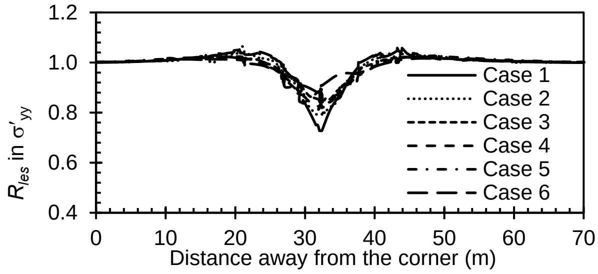
$$R_{les} = \frac{\sigma'_{OSF}}{\sigma'_{Normal}} \quad (1)$$

In which σ'_{OSF} means horizontal effective stress of soils at the depth of the failed strut with OSF. σ'_{normal} means horizontal effective stress of soils at the same selected depth with OSF case but none of strut fails.

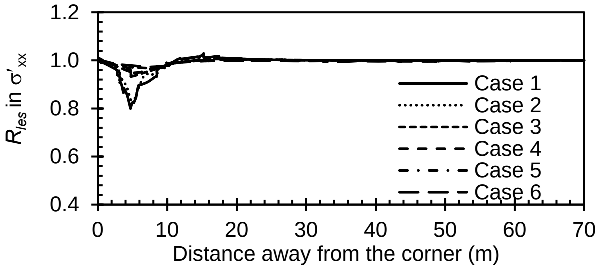
In order to represent the failed strut, said strut is removed from the model during the analyses for OSF case. Further, the model is simplified to have a failed strut in longitudinal direction only, not in transverse direction. Fig. 4 shows R_{les} in X and Y direction for cases having the failed strut at different locations (2 m from the corner and centre at the excavation). It is seen that R_{les} does reduce at a certain zone close to the failed strut so it implies that horizontal effective stress of soils within this "influence zone" is affected but said influence zone is comparatively larger for the failed strut at the centre of the excavation rather than the one close to the corner. It is anticipated that the corner effect is the reason leading to reduction of the influence zone but in general the impact from OSF on most of ground is insignificant. Moreover, the impact is likely to be more obvious in stress in longitudinal direction rather than transverse one. As the failed strut is in longitudinal direction, it is expected to be the reason for that.



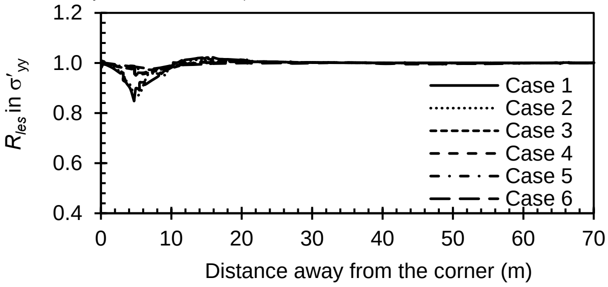
(a) Distribution of horizontal effective stress of soils in longitudinal direction (failed strut at centre of the excavation)



(b) Distribution of horizontal effective stress of soils in transverse direction (failed strut at centre of the excavation)



(c) Distribution of horizontal effective stress of soils in longitudinal direction (failed strut at 2 m from the corner of the excavation)



(d) Distribution of horizontal effective stress of soils in transverse direction (failed strut at 2 m from the corner of the excavation)

Figure 4 Impacts on soil stress distributions along the excavation from OSF case

It is also aware that a smaller R_{les} is observed for the case having a shallow excavation depth and it is suspected that a comparatively lower safety factor against push- in leads to a larger displacement of the soil mass but simultaneously changes soil stress at the rest condition originally toward the active condition which could possibly reduce horizontal effective stress.

4.2 Strut loads distribution

Both of Pong et al. (2012) and Goh et al, (2017) have discussed the impact from OSF on strut loads and evaluated whether the rest of struts are eligible to undertake load transferred. Since excavations in clay were selected for Pong et al. (2012) and Goh et al. (2017), a similar evaluation is thus delivered for excavations in sand in this study.

An excavation reported by Hsiung et al. (2016) was selected for this study and as indicated previously, the pit is 16.8 m deep and retained by 0.9 m thick, 32 m deep diaphragm wall with 4- level of struts. In order to give a clear picture of strut load distribution after an occurrence of OSF, additional dimensionless factor named "Ratio of load transferred (R_{lt})" is defined, as follows.

$$R_{lt} = \frac{F_{OSF}}{F_{normal}} \tag{2}$$

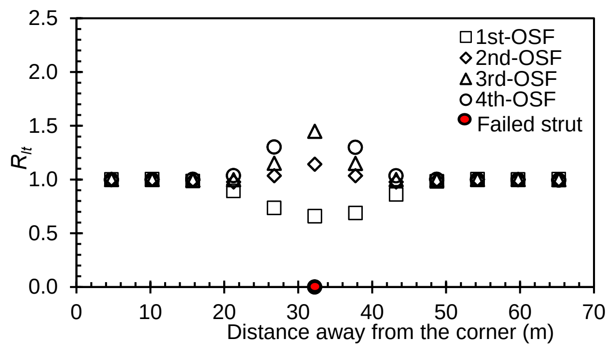
In which F_{OSF} means load on the strut with OSF case and F_{normal} means load on the strut without any failure of the strut.

It is first assumed that one- strut failure at 4th level strut at the centre of the excavation. Figure 5a shows the strut load distribution before and after occurrence of OSF using R_{lt}. As shown in Fig. 5a., the load on 1st level strut at the centre of the excavation drops significantly, up to approximately 44%.

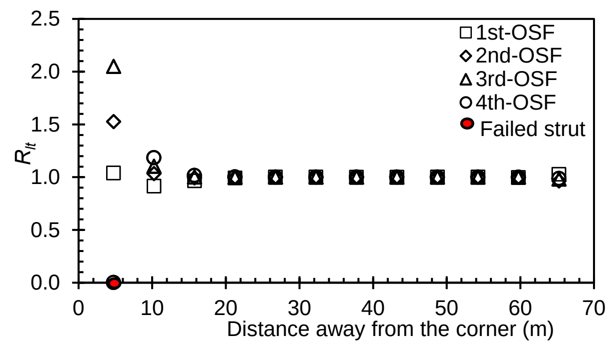
On the contrary, the load on both 2nd and 3rd level strut at the same location increase a lot, up to 30% and 50%, respectively. Similar impacts are likely to be observed to struts at 6 m away in horizontal direction from the place having the failed strut but the magnitude is much smaller. Rest of struts seem not to be affected by failure of the strut. It might be explained that additional load from the failed strut is transferred to two struts above at the same location, especially for the 3rd level strut which is only 3.35 m higher than the failed strut. Increasing of strut load might lead to shorten of the 2nd and 3rd level strut but might enlarge the 1st level strut due to change of wall shape and this might be the reason to be connected with drop of load of the 1st level strut.

Similar drop of load of the 1st level strut is reported by Goh et al. (2017) for excavation in soft clay with OSF case. Influence zone of struts from OSF analyzed by Goh et al. (2017) is similar too but R_{lt} is likely to be smaller for which a further study is essential to explore the reason.

Second, OSF was assumed to be set at 4th level strut close to the corner of the excavation (4 m away from the corner) and Figure 5b presents the load on struts. It is seen that only a column of struts close to the corner are influenced, though increasing in load on 3rd level strut up to 110% at the end. Unlike OSF at the strut at the centre of the excavation, the 1st level strut seems not to be affected at all. The corner of the excavation restrain development of strut load and displacement from OSF is expected to be the reason.



(a) *Impacts from OSF at the 4th level strut at the centre of the excavation*



(b) *Impacts from OSF at the 4th level strut close to the corner of the excavation*

Figure 5 Impacts from OSF on strut load

5. CONCLUSIONS

The following conclusions can be drawn from the results of this research.

1. Mechanism of the excavation in sand with one-strut failure (OSF) is explored. It is first seen that horizontal effective stress of soil does reduce at certain range close to the failed strut so it implies that horizontal effective stress of soils within this "influence zone" is affected but said influence zone is comparatively larger for the failed strut at the centre of the excavation rather than the one close to the corner. It is anticipated that the corner effect is the reason leading to reduction of the influence zone.
2. It is also aware that a larger reduction of horizontal effective soil stress is observed for the case having a shallow excavation depth and it is suspected that a comparatively lower safety factor against push- in leads to a larger displacement of the soil mass but simultaneously changes soil stress at the rest condition originally toward the active condition which can possibly reduce horizontal effective stress.
3. A 16.8 m deep pit with 4- level struts was selected to evaluate impacts from OSF on loads on the struts and it is understood that additional load from the failed strut is mainly transferred to the strut one-level above and the main reason is expected to be a comparatively shorter distance away from the failed strut. Up to 50% more load is transferred. On the contrary, 110% more load is transferred to the strut one- level above if the failed strut is located close to the corner of the excavation. However, in terms of magnitude of additional load on the strut and influence zone, the failed strut located close to the corner has much less impact and the restraints provided by the corner effect is anticipated to be the reason.

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