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UofKEJ Vol. 9 Issue 1 pp. 47- 51 (August 2019)

UNIVERSITY OF KHARTOUM ENGINEERING JOURNAL (UofKEJ)

# Numerical Analysis of Deep Excavation

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**Abstract:** Because of limited knowledge on experience on deep excavation analysis in Sudan, this study aimed to study numerical models for modeling deep excavation and adjacent buildings or public facilities near by the excavation. A series of parametric studies were conducted to evaluate the effect of wall stiffness and strut stiffness. The numerical analysis results showed that the increase of retaining wall stiffness or strut stiffness to reduce wall deformation is certainly effective, however does not have linear relationship. Last, based on the numerical results, the evaluation of adjacent building damage related to settlement induced by excavation and suggestions protection of adjacent buildings before and during excavation were discussed.

***Keywords:*** *deep excavation, numerical analysis, wall deformation, building damage*.

## 1.1 INTRODUCTION

To develop the cities with limited space, it is required to maximize the utility of every area. That leads to increasing deep excavation projects in center of big cities from time to time. Khartoum, as capital city of Sudan also needs to build deep underground basements and improve their city transportation system by constructing subways or Mass Rapid Transit (MRT) system that already famous in some other countries, and deep excavation will take the very important role in its construction.

A deep excavation is typically defined as an excavation in soil or rock that is deeper than 4.5 m. The first part of the deep excavation is to determine the geological conditions and subsurface soil information in site from previous literature and report. Therefore, due to limited knowledge on experience on deep excavation analysis in Sudan a specific study on deep excavation related to adjacent buildings or public facilities near the excavation including the research study of geotechnical subsurface condition to obtain reliable soil properties for design are necessary. It is very important to determine what kind of appropriate constitutive model and material parameters selected in the analysis that can represent real soil behavior.

The common deep excavation methods are full open cut method, braced excavation method, island excavation method, the anchored excavation method, top-down construction method, and zoned excavation method. The most common method is braced excavation method, however it depend on many factors, such as construction budget and period, existence and condition of adjacent building, and availability of construction equipment, area of construction site. A detailed description of deep exaction methods and their retaining walls are presented by Ou et al. [1]. Excavation analyses consist of stability analyses (i.e., ultimate failure, sand boiling, and uplift analyses), deformation analyses (i.e., to determine lateral deformation of retaining walls, heave of the excavation bottom, and settlement of the soil outside the excavation zone), and stress analyses (i.e., to find strut load, and bending moment, and shear of retaining walls).

For any deep excavation project, it is very important to know the characteristics of wall deformation and ground settlement because it is related to the response of the building surrounds them. These can be predicted by empirical correlations and also some series of Analysis methods such as finite element method. Clough and O'Rourke [2] and Ou et al. [1] predicted the wall deformation and ground surface settlement induced by excavation based on empirical and semi-empirical methods. All their empirical methods are developed based on the field observations of excavation case histories. Hsieh and Ou [3] proposed the ground settlement profiles that can be divided as two types: spandrel and concave type of settlement as shown in Fig. 1. The spandrel type of settlement will occur when the maximum ground surface settlement will be found near the retaining wall. However, the cantilever type of settlement produced when the maximum ground surface settlement found to be located at distance in back of the wall.

Clough and O'Rourke [2] demonstrated that under normal construction conditions, excavation in soft clay produce deflection of the retaining wall and leads to the concave type settlement. However, for sand soil will produce less deformation of the retaining wall and the spandrel type of settlement may be produced. Overall, these two types of ground surface settlement are mostly affected by the magnitude and shape of deformation of retaining wall.This study conducted a numerical model (PLAXIS program) for modeling deep excavation and adjacent buildings or public facilities near by the excavation. Parametric studies were conducted to evaluate the effect of wall stiffness, strut stiffness, soil- structure interfaces.

These parametric studies were proposed to benefit further design practices in Sudan to create more efficient and economical design. Based on the numerical analysis results, the evaluation of adjacent building damage related to settlement induced by excavation and suggestions protection of adjacent buildings before and during excavation are discussed.

## 1.2 NUMERICAL ANALYSES PROGRAM

A commercial Finite Element (FE) program, PLAXIS 2D v. 8.2, was used for the numerical analyses in this study. PLAXIS 2D has been widely used to analyze deep excavation problems to predict the behavior of retaining wall and ground settlement near by the excavation (e.g., Lim et al. [4]; Lu et al. [5]; Hwang et al. [6]). The FE method offers comprehensive information concerning stress, strain, force, and displacement at any location of interest.

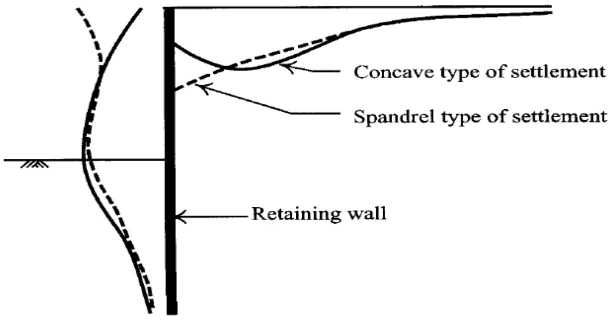


**Fig 1:** Types of Ground Surface Settlement

### 1.3 Model and Method of Approach

The geometry and material properties of the excavation model used in this study are presented in Fig. 2, where γ, ∅' and $S_u$ are the unit weight, friction angle and undrained shear strength of soils, respectively, N is SPT (Standard Penetration Test) value, and CH, CL are high and low plasticity clay soils, respectively. The excavation depth was 14.1 m and width was 27.8 m. The retaining wall was 70 cm thick and 30 m deep diaphragm wall. The excavation was carried out in four stages. Four levels of struts were installed. Along the excavation a surface load 14 kN/m$^2$) is taken into account to simulate adjacent properties or public facilities.

Hardening Soil (HS) model has been used as a soil constitutive model in this study. It was found that the Hardening Soil model had better ability to predict the stress-strain curves of granular soil at working stress condition than the Mohr-Coulomb model, a Linear elastic and perfect plastic model. The soil stiffness (*E*) was estimated using Japan Road Association (JRA) equation ($E_s$ = 2800 N), since the reliable laboratory data to obtain *E* value was not available and the stiffness parameter was also obtained using correlation from SPT-N value. The stiffness parameter in the PLAXIS program are $E_{50}^{ref}$ (is a reference stiffness modulus corresponding to the reference confining stress $p^{ref}$), $E_{oed}^{ref}$ (is the tangent stiffness at a major principle stress), and $E_{ur}^{ref}$ (is the reference Young's modulus for unloading and reloading).$E_s$ value obtained from the correlation was set as $E_{50}^{ref}$ . In the PLAXIS, a default setting $E_{50}^{ref} = E_{oed}^{ref}$ , $E_{ur}^{ref} = 3E_{50}^{ref}$ , and $p^{ref}$= 100. Table 1 summarize the estimated soil parameters for finite element analysis.

Diaphragm retaining walls were modelled as plate in PLAXIS. For the interaction between clay and concrete, the interface elements, $R_{inter}$, was selected equal to 1.0 as number suggested from PLAXIS. Table 2 present material properties of diaphragm wall.

Struts and were modelled as node-to-node anchor in PLAXIS. The struts load was computed using Peck's (1969) earth pressure method. The input load on the first, second, third, and forth level of struts are 340 kN/m, 530 kN/m, 400 kN/m, and 350 kN/m, respectively. Table 3 summarize material properties of the strut.

A 15-node triangular element with 12 stress points under plane strain conditions was designated for the soil element at the initial conditions of the FE mesh. The mesh coarseness was set as medium. Initial ground water level located 3.0 m below the ground surface and water pressure corresponding to water level inside and outside excavation was assigned as hydrostatic condition. The calculation process was performed using *staged construction calculation* as presented in PLAXIS to simulate the excavation at the final depth. *Staged construction* enables the activation or deactivation weight, stiffness, and strength of selected components of the finite element model.

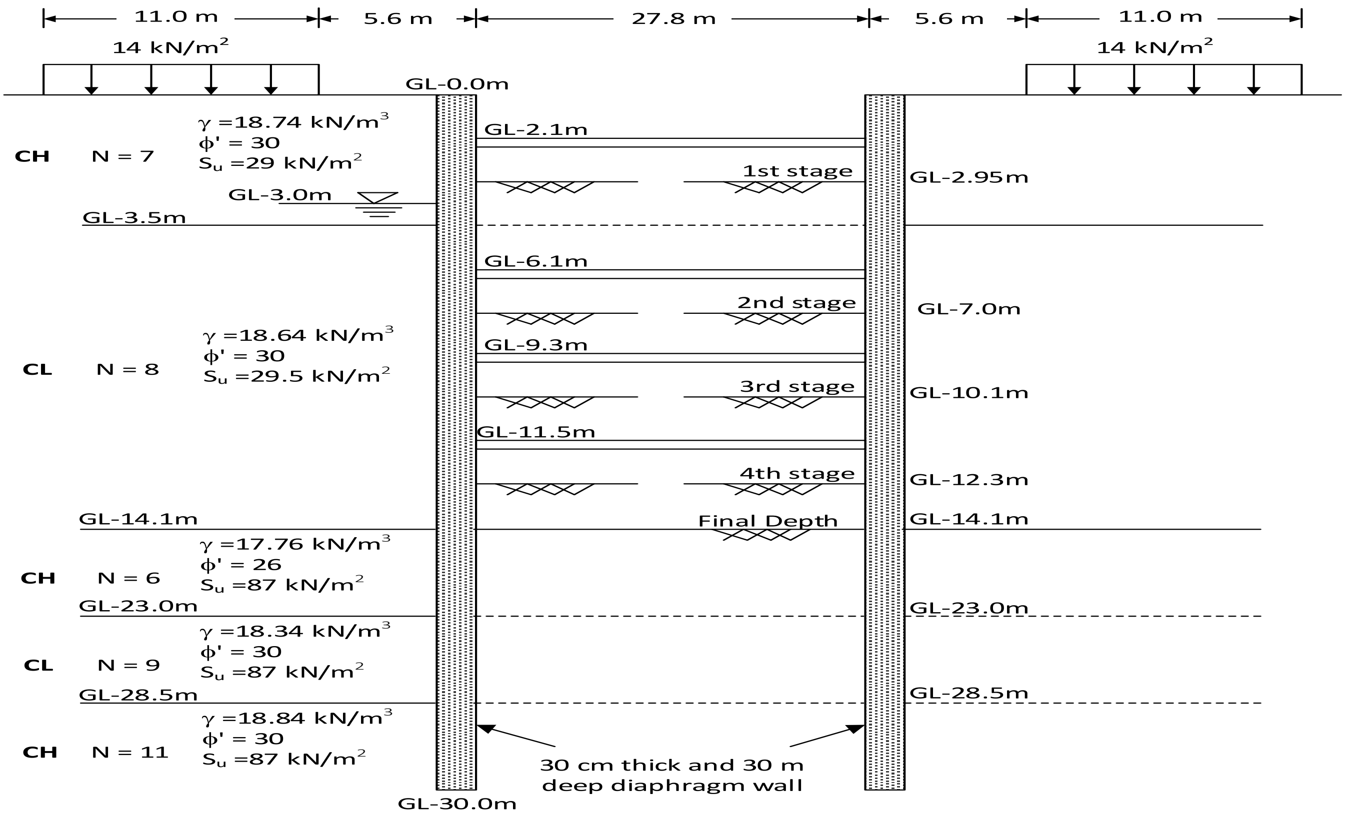


**Fig .2.** Geometry of Excavation Mode

**Table 1.** Material properties of soils used in the model

| Level (m) | Soil Type | SPT-N | γ (kN/m³) | $S_u$ (kN/m²) | ϕ' deg. | *E* (kN/m²) | | | Poisson's ratio ($\nu_{ur}$) | failure ratio ($R_f$) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | $E_{50}^{ref}$ | $E_{oed}^{ref}$ | $E_{ur}^{ref}$ | | |
| 0-3.5 | CH | 7 | 18.74 | 29 | 30 | 20000 | 20000 | 60000 | 0.2 | 0.9 |
| 3.5-14.1 | CL | 8 | 18.64 | 29.5 | 30 | 22000 | 22000 | 66000 | 0.2 | 0.9 |
| 14.1-23 | CH | 6 | 17.76 | 87 | 26 | 18000 | 18000 | 54000 | 0.2 | 0.9 |
| 23-28.5 | CL | 9 | 18.34 | 87 | 30 | 24000 | 24000 | 72000 | 0.2 | 0.9 |
| 28.5-40 | CH | 11 | 18.84 | 87 | 30 | 30000 | 30000 | 90000 | 0.2 | 0.9 |

**Table 2.** Material properties of diaphragm wall

| Parameter | Value |
|---|---|
| Material type | Elastic |
| Normal stiffness, *EA* | 9.5 x 10⁶ kN/m |
| Flexural rigidity, *EI* | 3.88 x 10⁵ kNm²/m |
| Equivalent thickness, *d* | 0.7 m |
| Weight, *w* | 10.0 kN/m/m |

**Table 3.** Material properties of the strut

| Parameter | Value |
|---|---|
| Material type | Elastic |
| Normal stiffness, *EA* | 2.0 x 10⁶kN |
| Spacing out plane $L_s$ | 5.0 m |

### 1.4 Wall Deformation Induced By Excavation

Fig. 3 shows finite element results of the wall deformation. The finite element results showed that the maximum wall deformation at final excavation stage was 6.8 cm (left wall) and located near the excavation zone. The maximum wall deformation was approximately 0.27% of excavation depth ($H_e$). The value of wall deformation is still in the range provided by Ou et al. [1] who suggested the range of maximum lateral wall deflection ($\delta_{hm}$) is within 0.2% 0.5 %$H_e$ and occurs near the excavation surface.

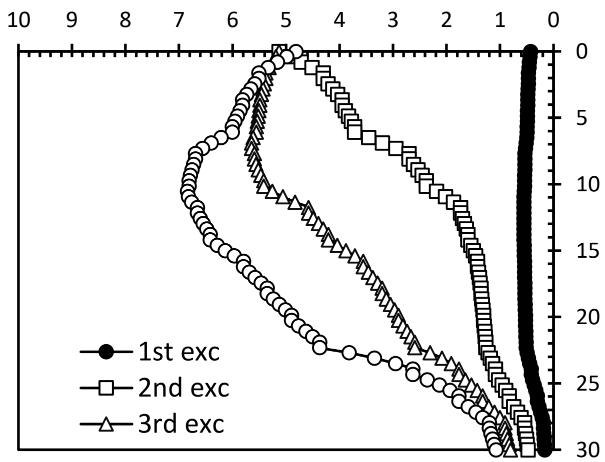


**Fig .3.** Wall Deformation at Left Diaphragm Wall

### 1.5 Ground Surface Settlement

Fig. 4 illustrates ground surface settlement**.** The maximum ground surface settlement at final excavation stage was about 6.5 cm behind left wall. The ground settlement was concave type and the ratio of horizontal movement and vertical movement was larger than 1.0. This value agree with Ou et al. [1] who established relationship between the maximum ground surface settlement and the excavation depth from the excavation histories in Taipei, Chicago, and Oslo and found that $\delta_{vm}/\delta_{hm}$ = 0.5 for sandy soils and $\delta_{vm}/\delta_{hm}$ = 0.75 for clays. But for very soft soils, $\delta_{vm}/\delta_{hm}$ may be equal or larger than 1.0 (note: $\delta_{vm}$ is maximum ground surface settlement and $\delta_{hm}$ is maximum lateral wall deformation).

Nicholson [7] and Ou et al. [1] proposed that the maximum ground surface settlement of concave type would occur at distance of 0.5 $H_e$. In this study the maximum ground surface settlement was observed at distance 10 m behind the wall as shown in the Fig. 4.

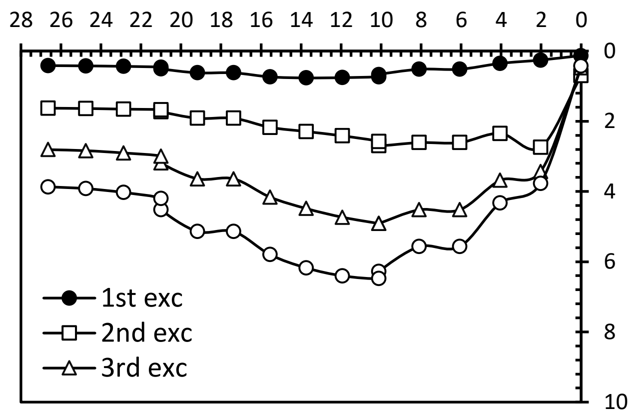


**Fig .4.** Ground Surface Settlement behind Left Diaphragm Wall

### 1.6 Bending Moments

Significant benefits of finite element modelling structures such the deep excavations is that it is possible to investigate the bending moments and structural forces which can be used to check that they have sufficient capacity to withstand the resulting stresses. Maximum bending moment was about 622.7 kN.m for the left and right wall.

### 1.7 Effect of Wall Stiffness

The variation of +/- 25% of the wall stiffness as compared to the original analysis has been assumed. Figs. 5 and 6 show the effect of wall stiffness on wall deformation and ground settlement at the final stage. In general, the deformation of retaining wall will decrease with increase the wall stiffness. However, as shown in the Fig. 5 the amount of decrease does not have a linear relationship with the increment of stiffness. These results agreed with the results obtained by Hsieh and Ou [3]. They found that the increase of wall thickness or wall stiffness to reduce wall deformation is certainly effect, but only to a certain extent.

### 1.8 Effect of Strut Stiffness

Fig. 7 and 8 present the results of strut stiffness variation at the final stage. The strut stiffness has been varied by +/- 25%. The results in Fig. 7 showed that if strut stiffness reduced by 25%, the significant observation of the maximum wall deformation takes place at top of the retaining wall. This result agree with Ou *et al*. [8] who stated that if the stiffness of struts are not high, the compression of the struts should be quite large. There will be larger wall displacement around the contact points during the second and third stages of excavation.

The final deformation pattern of the retaining wall will be close to that of cantilever type and the maximum deformation will be produced at the top of the retaining wall. Also Ou et al. [9] demonstrated that if the struts are placed at deeper levels with the earth pressure; the preload of struts is not able to push the outward wall easily. Thus the increasing of strut preload does not decrease the wall deformation.

### 1.9 ADJACENT BUILDING DAMAGE

Evaluation of ground settlement and its pattern is essential as a first step to predict the building damage. Thus, if the maximum ground surface settlement produced is too large, it will cause the component of adjacent building, such as beams, columns, walls, and foundations cracked or even create building damage. In this study the finite element results showed that the maximum ground surface settlement behind the wall induced by excavation is about 6.5 cm. (left diaphragm wall) (concave type). The influence distance of ground settlement is about 26.6 m behind the diaphragm wall. This data can be used for preliminary estimation of the building damage.

Yen and Chang [10] proposed allowable settlement for reinforced concrete structures as shown in Table 4.From the date presented in the table, if the calculation or measurement result of settlement exceed the number provided in the table, the damage is predicted to risk the adjacent buildings and some protection may be required. Bjerrum [11] presented the relations between the angular distortion and the damage of building as shown in Table 5.The angular distortion also can be used as the preliminary estimation of the building damage. In this study, the ratio of angular distortion (β) can be estimated from the ground settlement of excavation resulted obtained from finite element analysis in the model. These results were used to predict the building damage or public facilities due to the excavation.

As presented in Fig 9, the distributed load or frame structure with 11 m length was assumed stand 5.6 m behind the left or right diaphragm wall. Due to the settlement induced by the excavation, the building or public facilities is predicted to experience the settlement as well. As shown in Fig. 9, β can be estimated as ratio between the differential settlement between point A and B ($\delta_{AB}$) and the length of the structure (L). $\delta_{AB}$ obtained from the analysis at center of distributed load was about 1.0 cm, so as the result β = 1/500 was obtained. This angular distortion obtained will not create any damage to the structure comparison to the date presented in Table 5.

Generally the protection of adjacent building during excavation can be divided into three procedures: before excavation plan (i.e., comprehensive geological investigation, evaluation the influence range of excavation, and measurement the existing cracks if there); (b) monitoring during the construction (i.e., monitoring the deformation of retaining wall and ground settlement), and (c) compensation after damages have been done (i.e., prevent the damage from expanding).

Therefore, after estimating the type of damage, the possible protection building can be applied to prevent the damage. As discussed before the increasing retaining wall stiffness to decrease wall deformation does not help much. Ou et al. [1] suggested that the effective procedure is to decrease the horizontal, vertical span of struts and stiffness of struts.

Additionally, utilizing auxiliary method such as ground improvement, installed the counterfort wall, cross wall, and underpinning also can help to decrease the wall deformation or ground settlement [9].Overall, the investigation of adjacent properties condition or public facilities before designing an excavation project is required to evaluate the allowable settlement which leads to determine the type of retaining wall and strutting systems and selection of auxiliary methods.

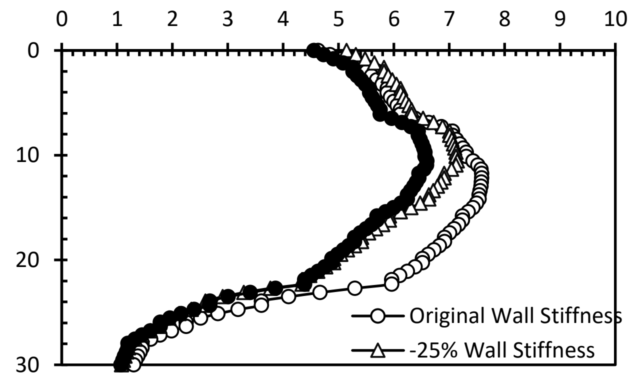


**Fig .5.** Wall Deformation on Left Diaphragm Wall - Effect of Strut Stiffness

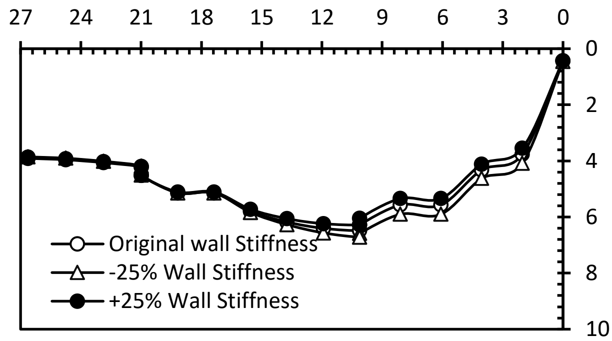


**Fig .6.** Ground Settlement on Left Diaphragm Wall - Effect of Wall Stiffness

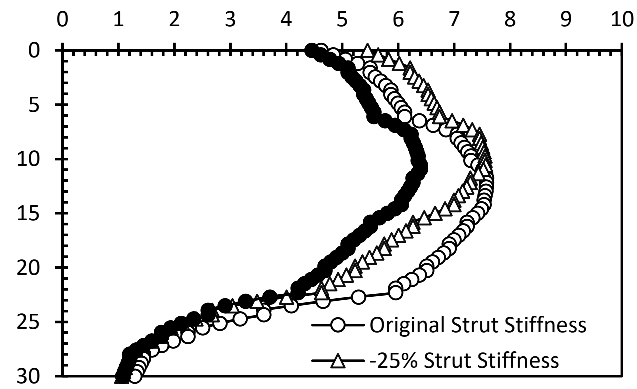


**Fig .7.** Wall Deformation on Left Diaphragm Wall - Effect of Strut Stiffness

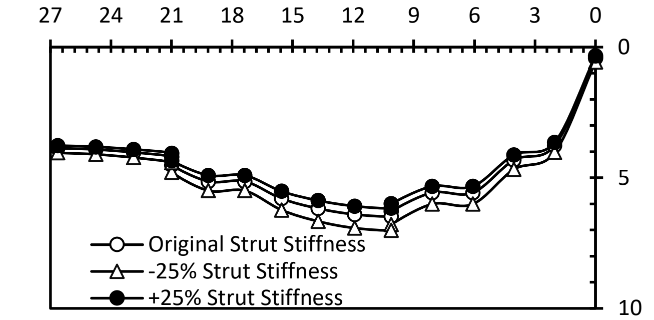


**Fig 8:** Ground Settlement on Left Diaphragm Wall - Effect of Strut Stiffness

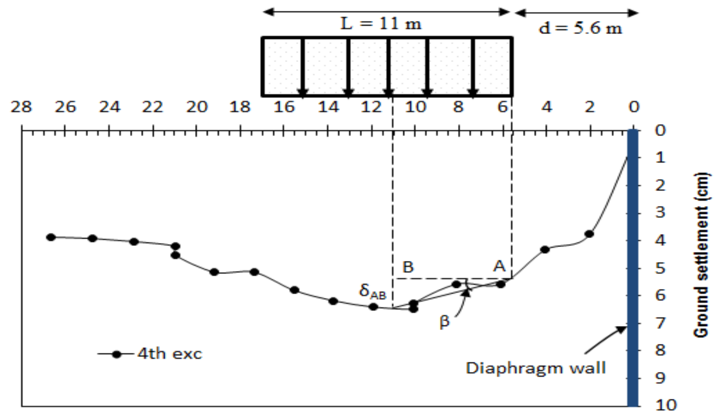


**Fig 9:** Angular Distortion of Building or Public Facility near an Excavation

**Table 4.** Allowable settlement for reinforced concrete structures [10]

| Type of foundation | Soil | Total settlement (cm) | Differential settlement (cm) |
|---|---|---|---|
| | | 2.5 | 2.0 |
| Individual foundation | Sand | 5.0 | 3.0 |
| | | 3.0 | - |
| Individual foundation | | 7.5 | - |
| | Clay | 10.0 | - |
| | | 5.0 | 2.0 |
| | | 5.0-7.5 | 3.0 |
| Mat foundation | Sand | 6.0-8.0 | - |
| | | - | 3.0 |
| | | 7.5-12.5 | 4.5 |
| Mat foundation | Clay | 20.0-30.0 | - |
| | | - | 5.6 |

**Table 5.** Limiting values of angular distortion [11]

| Angular Distortion | Type of Damage |
|---|---|
| 1/750 | Dangerous to machinery sensitive to settlement |
| 1/600 | Dangerous to frames with diagonals |
| 1/500 | Safe to limit assure no crack of buildings ( factor of safety included) |
| 1/300 | First cracking of panel walls ( factor of safety not included) |
| 1/300 | Difficulties of overhead cranes |
| 1/250 | Tilting with high rigid buildings becomes visible |
| 1/150 | Considerable cracking of panel and brick walls |
| 1/150 | Danger of structural damage to general building |
| 1/150 | Safe limit for flexible brick walls (factor of safety not included) |

## 1.10 CONCLUSIONS

This paper present numerical models for modelling deep excavation and adjacent buildings or public facilities near the excavation. Deep excavation necessarily gives rise to movement of the soil near the excavation site. If the movement or ground surface settlement is too large, it will damage neighbouring building or public facilities. Therefore, estimating wall movement and ground surface settlement, and condition of adjacent properties and public facilities before designing an excavation project are required to prevent the damages.

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