International Journal of Civil Engineering

Geotechnique

The performance of buildings adjacent to excavation supported by inclined struts

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Received: November 2013, Revised: June 2014, Accepted: October 2014

Abstract

Limitations in the design method used for the support systems of urban buildings make them vulnerable to damage by adjacent excavations. This paper examines a traditional system used to support excavation sites and adjacent buildings in which inclined struts are connected to the wall or foundation of the adjacent building. This method can be considered to be a type of shoring or underpinning. The performance of buildings and the criteria for deformation control during excavation are introduced. Next, a 2D finite element analysis is presented in which an excavation is modeled considering the parameters from the adjacent building and the inclined struts. The numerical model is capable of simulating the overall excavation and installation of the support system. The soil is modeled using an elastic perfectly-plastic constitutive relation based on the Mohr-Coulomb criterion. The finite element model is validated using Rankine earth pressure and in situ data was measured during an excavation. The effect of different variables on performance and acceptable limits for the inclined strut are discussed. The model used for the parametric study shows the influence of the characteristics of the adjacent building, soil parameters, geometry of excavation, type of excavation and effect of strut installation. It was found that one type of strut arrangement produced the best possible result. The results can be used as a primary approximation of small-to-medium depth excavations in which struts are used to reduce the deflections.

Keywords: *Excavation adjacent to buildings, performance base design, 2D FEM, building deflections, inclined strut.*

[DOI: 10.22068/IJCE.13.1.1]

1. Introduction

With the rapid development of urban construction, engineers and researchers have examined types of excavations performed in urban areas and the design of braced excavations. The density of structures in a typical urban environment increases the importance of the type of excavation on the adjacent structures. The inclined strut is one type of support system used for excavation. This type is common in current practice in Iran as a traditional shoring or underpinning method. [1]. Shoring is a form of temporary support that can tie existing buildings to the adjacent excavation to avert damage. Underpinning is a temporary support that transfers the load carried by a foundation from its bearing level to a lower depth [2]. This technique and its effect on adjacent buildings are schematically illustrated in Fig. 1. A number of studies have been done on the mechanism of struts and the effect of different variables on the performance of the excavation support system [1], [2], [3], [4]. In this paper, excavation using inclined struts is investigated based on performance-based design of the adjacent building.

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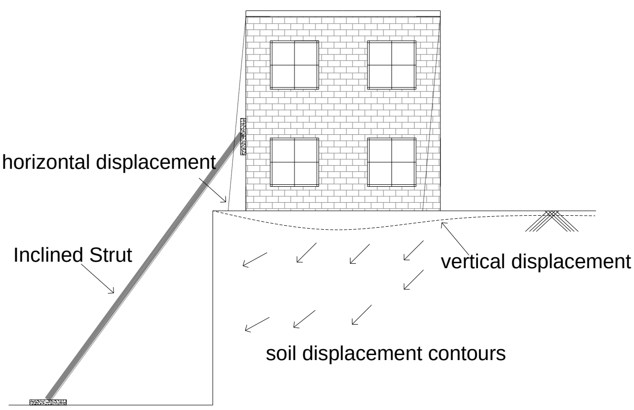


Fig. 1 Schematic figure of 'inclined strut' method and excavation effects on buildings

2. Adjacent Building Performance Criteria in Excavation

Excavations are often constructed adjacent to other buildings. To protect these existing buildings, performance-based design is an approved approach for the design of excavations [5]. Performance-based design considers different performance criteria and assesses design parameters to satisfy them over the service life of the excavation [6]. A comprehensive understanding of the characteristics of the wall and ground deformation is important to performance-based design. The excavation is governed by complex factors, such as ground condition, type of retaining structure, stiffness of supports and building conditions [5]. Performance-based design satisfies multiple performance targets in the best possible way. This approach takes advantage of improvements in the performance method and the computational tools used for analysis [6]. Compared with conventional specification-based designs, performance-based design is a more general approach in which the design criteria are expressed in terms of performance requirements when the structure is subjected to different loads [7].

A number of evaluation criteria have been proposed for estimating the potential of building damages or performance levels of adjacent buildings. Later on, vertical and horizontal displacements were used to consider the performance level of neighboring building. The damage levels were determined based on the observed damage for field data and the observed and calculated crack width criteria as proposed by Burland et al [8]. Based on the damage classification, damage categories ranged from "Very Severe" to "Negligible" as explained in Table 1 [9].

Table 1 Building damage classification [8]

Damage category	Category of damage	Description of typical damage	Approx. crack width (mm)	Limiting tensile strain ε_{crit} (%)
0	Negligible	Hairline cracks.	<0.1	<0.05
1	Very slight	Fine cracks that can easily be treated during normal decoration	<1	0.05-0.075
2	Slight	Cracks easily filled. Redecorating probably required.	<5	0.075-0.15
3	Moderate	The cracks require some opening up and can be patched by a mason. Recurrent cracks can be masked by suitable linings. Repointing of external brickwork and possibly a small amount of brickwork to be replaced.	5-15 or number of cracks >3	0.15-0.3
4	Severe	Extensive repair work involving bricking out and replacing section of walls, especially over doors and windows.	15-25 but also depends on number of cracks	>0.3
5	Very severe	This requires a major repair job involving partial or complete rebuilding.	Usually >25 but also depends on number of cracks	

Boscardin and Cording [10] illustrated the importance of horizontal ground strain, (ε_l), in initiating damage. Fig. 2 introduces deflections parameters used in damage criteria. Fig. 3(a) indicates onsets of lateral strain (ε_l) and angular distortion (β) relative to degree of damage. By measuring β and ε_l, the degree of damage could be estimated based on Boscardin and Cording method. Burland studies included lateral strain based on Boscardin and Cording method and improved different values of critical strain related to damage categories [11]. Fig. 3(b) shows the Burland damage criteria. These two damage categories are based on the criteria proposed by Skempton and McDonald and Bjerrum [12].

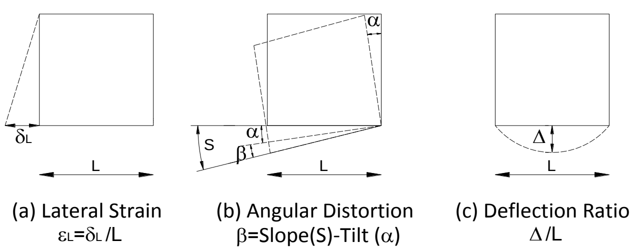
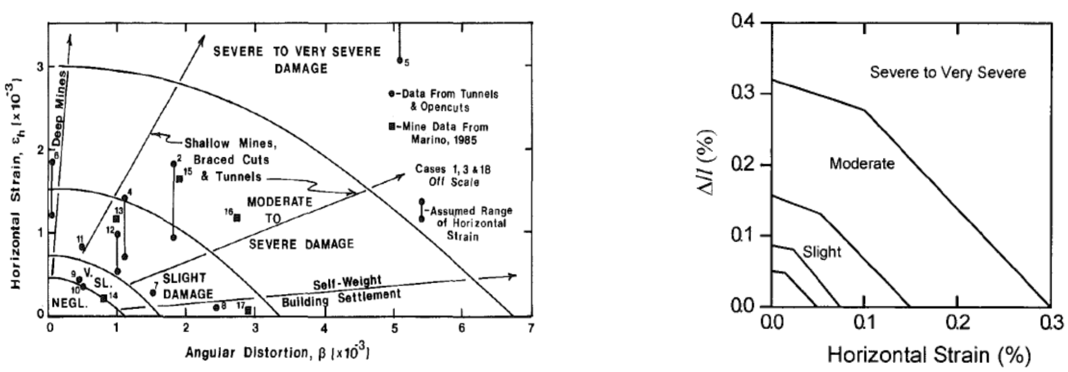


Fig. 2 Deflection parameters used in damage criteria



(a) (b)

Fig. 3 Damage level a) in relation to β, ε_l (Boscardin and Cording 1989), b) in relation to horizontal strain, Δ/L (Burland 1995)

[DOI: 10.22068/IJCE.13.1.1]

Devriendt et al [13] demonstrated that comparing Fig. 3(a) and (b) for assessing damage levels of buildings, where the shear mode of deformation of building is dominant, the both methods converge on similar results. Boscardin and Cording method allows consideration of bending and shear modes of deformation and both hogging and sagging forms of movement. The parameter, *angular distortion* is preferred to define deformation caused by settlement or heave rather than deflection ratio as proposed by Burland. Therefore in the presented research, Boscardin and Cording damage categories (Fig. 3(a)) used as a performance criterion to discuss the result of numerical analysis.

3. Numerical Analysis

In the presented research, two dimensional total stress elasto-plastic analyses was performed to examine the effect of excavation induced movements on the adjacent buildings after installation of inclined struts in excavation. Numerical simulations were carried out using finite element method. The finite element simulation involves the following steps: (i) element discretization, (ii) primary variable approximation, (iii) element equations, (iv) global equations, (v) boundary conditions, (vi) solve the global equations. To determine the global equations for linear material behavior, the principle of minimum potential energy is invoked for elements. Global potential energy is found by the sum of the potential energies of the separate elements [14]. Moreover simulation of excavation in a finite element analysis can be explained as follows. When a portion of soil excavated, displacements and changes in stress replaced by traction (T) which applied to soil. Therefore simulation of stage of excavation involves determination of the traction at the new soil boundaries, determination of the soil stiffness, and application of tractions, -T, to the new soil boundaries. This process in finite element modeling involves determination of the nodal forces which are equivalent to the traction [14].

However excavation is a three-dimensional problem, the 3D analysis is much expensive than the 2D analysis in terms of computation time and required memory. Ghahreman showed that the differences between the results of 3D model, in middle of excavation wall exception of the nodes on the front and back plane in Z direction, and the 2D model are negligible [15]. In this study two-dimensional numerical simulations were carried out using ABAQUS v.6.10 [16].

3.1. Description of model details

Fig. 4 shows the finite element mesh. Soil was modeled using plane strain elements, whereas neighboring building was modeled as a bearing wall with the assumption of continuous wall and modeled by plane stress elements. Soil elements were rectangular with four nodes and four integration points, and the Gaussian integration method was applied to them. A uniform mesh was used for the bearing wall composed of elements as large as the American standard brick size of 57×203 mm [15]. The inclined struts were modeled using beam elements. A large zone was selected to avoid any measurable effects from the boundary in the final results. To minimize boundary effects, the vertical boundary at the far ends was set almost as 3 times of excavation's width from the center of excavation and horizontal boundary at the bottom of model was set 3 times of excavation's height from the bottom of excavation. It was assumed that vertical boundary to be free in vertical direction and restricted in horizontal direction. The bottom horizontal boundary was restricted in both horizontal and vertical directions. The boundary condition of model is also shown in Fig. 4.

Mohr-Coulomb constitutive model was chosen for soil elements. Wall and strut were simulated as linear elastic materials with no failure criterion. Table 2 summarizes the properties and parameters used for the numerical parametric studies. In modeling stages, the in-situ horizontal and vertical stresses were generated and the building was applied to model. The wall was located on the ground surface with no embedded footing. The interface between the structure and the soil elements was modeled by contact elements. Excavation stages and installation of supports were modeled according to common practice as shown in Fig. 5.

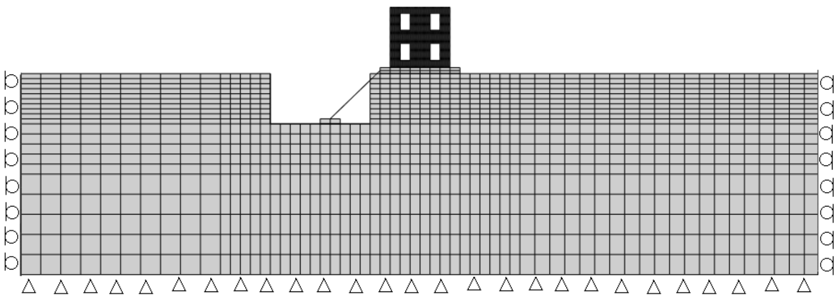


Fig. 4 Finite element mesh used for the hypothetical excavation case

Table 2 The parameters of soil and struts used in numerical modeling

Parameter	c (kPa)	ϕ (degree)	H (m)	B (m)	E_{soil} (MPa)	ν	γ_{soil} (kg m^{-3})	E_{steel} (MPa)	$E_{concrete}$ (MPa)
Amount	75	30	5	10	100	0.35	2000	2.0×10^5	2.0×10^4

[DOI: 10.22068/IJCE.13.1.1]

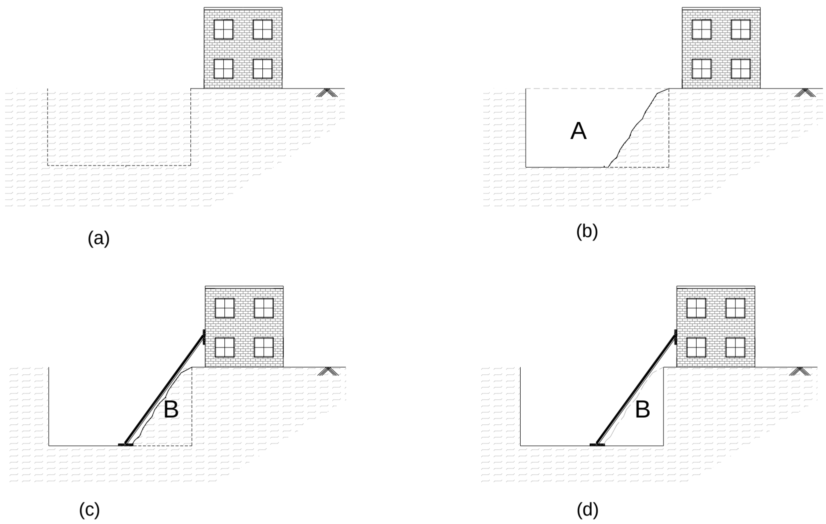


Fig. 5 Traditional excavation procedure (a) before excavation, (b) excavation zone A (stage 1), (c) installation of strut (stage 2), (d) excavation zone B (stage 3)

This study includes a series of analysis which present a parametric study to show the effect of different variables on the performance of adjacent building and also the limits which inclined struts have acceptable performance.

3.2. Validation of the numerical model

The numerical model was validated by data obtained from field measurements undertaken during the study. Since the field measurements were done only for one case, additional data was also used for model validation. Due to the unavailability of published data for excavation using inclined struts for adjacent buildings, soil mechanic problems were used to validate the model.

3.3. Validity of model to produce Rankine earth pressure

To examine the validity of model, simple retaining wall subjected to two types of translation was modeled: (i) Retaining wall translating horizontally; (ii) Retaining wall rotating about its base.

Both of problems were examined with the wall moving (0.5%*H* for active condition, *H* is wall height) away from or toward (3.5%*H* for passive condition) the retained soil mass. Details of parameters used in numerical model are presented in Table 3. The results of analysis are compared to known closed form solution (Rankine method) for retaining wall pressure in Fig. 6. It shows that the numerical results are consistent well with the closed form Rankine pressures. The difference in top of the wall in active condition and in base of the wall in passive condition arises because of the limitation of wall displacements to reach active or passive condition.

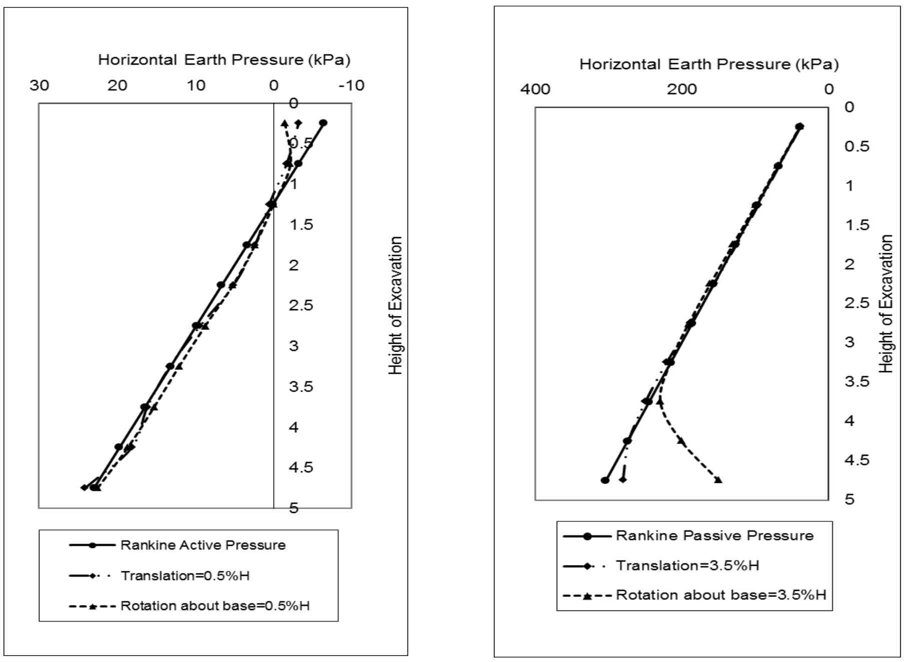


Fig. 6 Comparison Rankine closed form solutions with numerical model simulating (a) active and (b) passive retaining wall

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Table 3 The parameters of soil and wall in model validation

H(m)	c(kPa)	ϕ(degree)	E(MPa)	ν	K_0	K_a	K_p
5	7	30	17.5	0.35	1-sinϕ	$\frac{1-sin\varphi}{1+sin\varphi}$	$\frac{1+sin\varphi}{1-sin\varphi}$

3.4. Validity of model to produce measurement undertaken by authors

To illustrate the validity of the finite element model, field measurements of an excavation supported using inclined struts were used as reported by Sabzi and Fakher [17]. The depth of excavation was 3 m, the width was 14 m and the length was 21 m. The soil at the excavation site was sand and gravel. The soil parameters are shown in Table 4. Fig. 7 is a photograph of the excavation and Fig. 8 depicts a 3D view of the excavation, support system, neighboring structures and the instrumentation. Optical survey points on the excavation wall and buildings were used to monitor displacement. Strain gauges and load cells were used to measure strut loads. The numerical model was verified using data from the excavation. Fig. 9 shows the horizontal wall movement observed at the northern wall during excavation and compares wall deflection with field observations and FE model predictions. The results show that the FE model predictions are in good agreement with the measurements and can predict wall deflections reasonably.

The differences between the results of analysis and the field observations likely result from uncertainty when determining soil parameters and an insufficient number of survey points on the wall. Excavation is a 3D problem with complex soil-structure-strut interaction, but the configuration used for numerical modeling in this paper is 2D. In 2D analysis, the effect of the structures and struts on displacement in the out-of-plane direction are ignored, but could create small differences.

Fig. 7 Photo of excavation

Table 4 Soil parameters of excavation

Ks (kg/cm^3)	γ (kg/m^3)	ϕ (degree)	c (kPa)	E (kg/cm^2)
1.2	1900	35	30.0	700

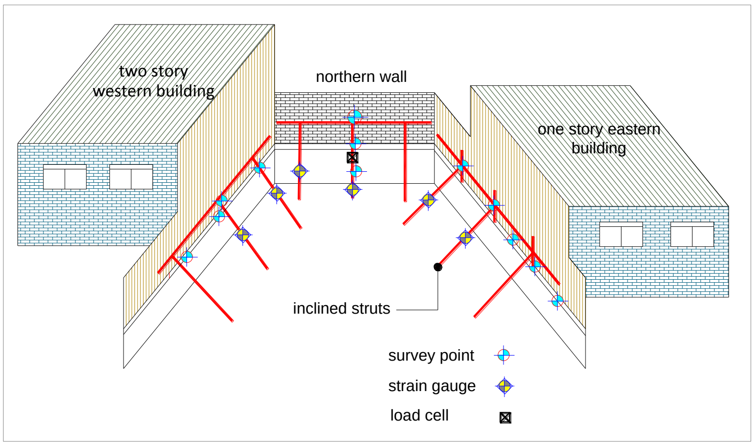


Fig. 8. 3D view of excavation and instrumentation

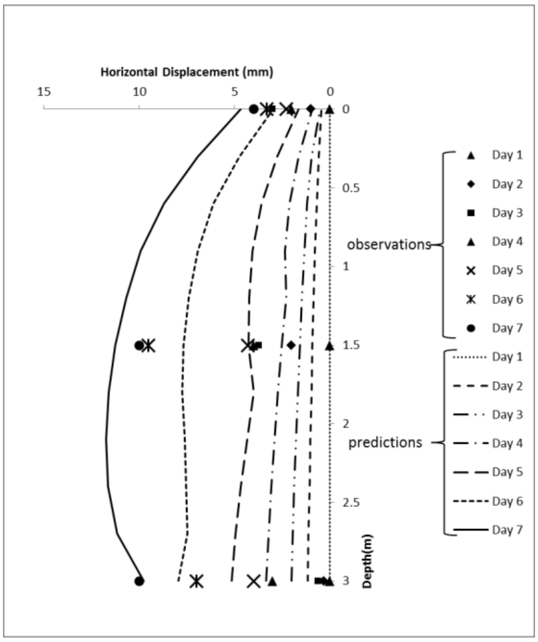


Fig. 9. Comparison of northern wall deflections between observations and numerical results at excavation days

4. Investigation of Governing Parameters

A comprehensive study on the effect of governing parameters on the performance of building and inclined strut in excavations contains investigation of (i) the parameters of adjacent building, (ii) soil parameters, (iii) geometry, (iv) procedure of excavation and (v) the

[DOI: 10.22068/IJCE.13.1.1]

parameters of inclined struts. To investigate the effect of parameters on the performance of building, the angular distortion/lateral strain is evaluated [18]. Boscardin and Cording criterion is based on the concept that a structure is deformed by the combination of angular distortion and lateral strain, and the maximum strain on the structure determine by a principal strain create by both the angular distortion and the lateral strain. Angular distortion and lateral strain can be determined by measuring vertical and horizontal displacements at the corners, A, B, C, and D of a building frame as shown in Fig. 10 [18].

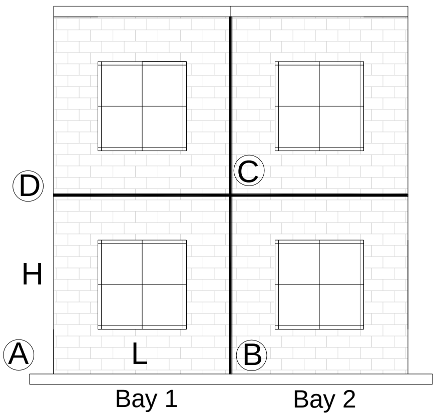


Fig. 10. Corners of the wall used for building damage estimation

Determination of the state of strain in building wall is done by measuring the vertical (A_v, B_v, C_v, D_v) and lateral displacements (A_l, B_l, C_l, and D_l) at the four corners (A, B, C, D) of a section of the wall (Fig. 10). The angular distortion and lateral strains were determined for the first bay (Bay 1) where the damage was concentrated. From these measurements, the following terms are defined to be used in damage determination [18].

Slope is the change of gradient at base over the length L of the section and is defined as:

$$Slople = \frac{A_V - B_V}{L} \tag{1}$$

Tilt is the rigid body rotation of the section and defined as:

$$Tilt = \frac{(C_l - B_l) + (D_l - A_l)}{2H} \tag{2}$$

Angular distortion is the shearing distortion of the section and defined as:

$$\beta = Slople - Tilt \tag{3}$$

Lateral strain at top $\varepsilon_{lat}T$ is the change of lateral displacement at the top over the length L of the section and defined as:

$$\varepsilon_{lat}(T) = \frac{D_l - C_l}{L} \tag{4}$$

Lateral strain at base $\varepsilon_{lat}F$ is the change of lateral displacement at the base over the length L of the section and defined as:

$$\varepsilon_{lat}(F) = \frac{A_l - B_l}{L} \tag{5}$$

ε_{lat} that used in this analysis defined as:

$$\varepsilon_{lat} = \frac{\varepsilon_{lat}(T) + \varepsilon_{lat}(F)}{2} \tag{6}$$

The effects of various parameters are shown in Fig. 11–15. In these figures, ground surface settlements, horizontal deflection of the excavation wall, deformation of structure and strut stresses in excavation time are shown. Deformation of structure can be described quantitatively using deflection parameters. Deflection parameters of neighboring building are shown in Boscardin and Cording diagram.

Characteristics of adjacent building

To investigate the effect of building, three parameters are considered: (i) stiffness of structure, (ii) opening ratio (the ratio between the total area of opening and the total area of the wall) and (iii) ground-structure interface. The analyses in this set are listed in Table 5 and are explained as follows.

Stiffness of structure: In order to get a more realistic response from the linear elastic material model, three different values are defined for wall stiffness in analysis sets and recognized as stiff (E_{wall}=3.4 ×10^6kPa), soft (E_{wall}=3.4 ×10^5 kPa) and very soft (E_{wall}=3.4 ×10^4 kPa). These values are selected based on the studies presented by Ghahreman [15]. (ii) Opening ratio: In modeling a wall with opening, the stiffness depends not only on the modulus of elasticity but on the opening ratio. Two opening ratio are employed to examine its effect. Small opening (ρ_1= 0.189) and large opening (ρ_2= 0.264). (iii) Ground–structure interface**:** In analyses the wall is located on the ground surface with no embedded footing. Two different methods are used to model interface. These are fully bonded interface, and frictional contact interface with ϕ interface=30° [15].

Table 5 Adjacent building parametric analysis

Number	Analysis	stiffness	Opening ratio	interface
1	NB00	Stiff	ρ_1	fully bonded
2	NB01	Soft	ρ_1	fully bonded
3	NB04	Very soft	ρ_1	fully bonded
4	NB02	soft	ρ_2	fully bonded
5	NB03	soft	ρ_1	frictional contact

Fig. 11 shows the results of analysis. Analyses show that stiffness of structure has no serious effect on ground surface settlement and horizontal wall deflection. The

[DOI: 10.22068/IJCE.13.1.1]

change in maximum ground surface settlement and horizontal wall deflection with the considerable increase up to one hundred orders of magnitude in structure stiffness (3.4 $\times 10^4$ kPa to 3.4 $\times 10^6$ kPa) is marginal, however the less the structural stiffness, the larger the wall and the ground movements. Fig. 11(c) shows that stiffness of structure has negligible effect on the strut load. Though results indicate that decrease in structure stiffness up to 99% (one hundred orders of magnitude) , result in 10% larger strut loads. Fig. 11(d) indicates that decreasing stiffness of structure substantially increases the magnitude of the deflection parameters and subsequently increases damage level in adjacent building.

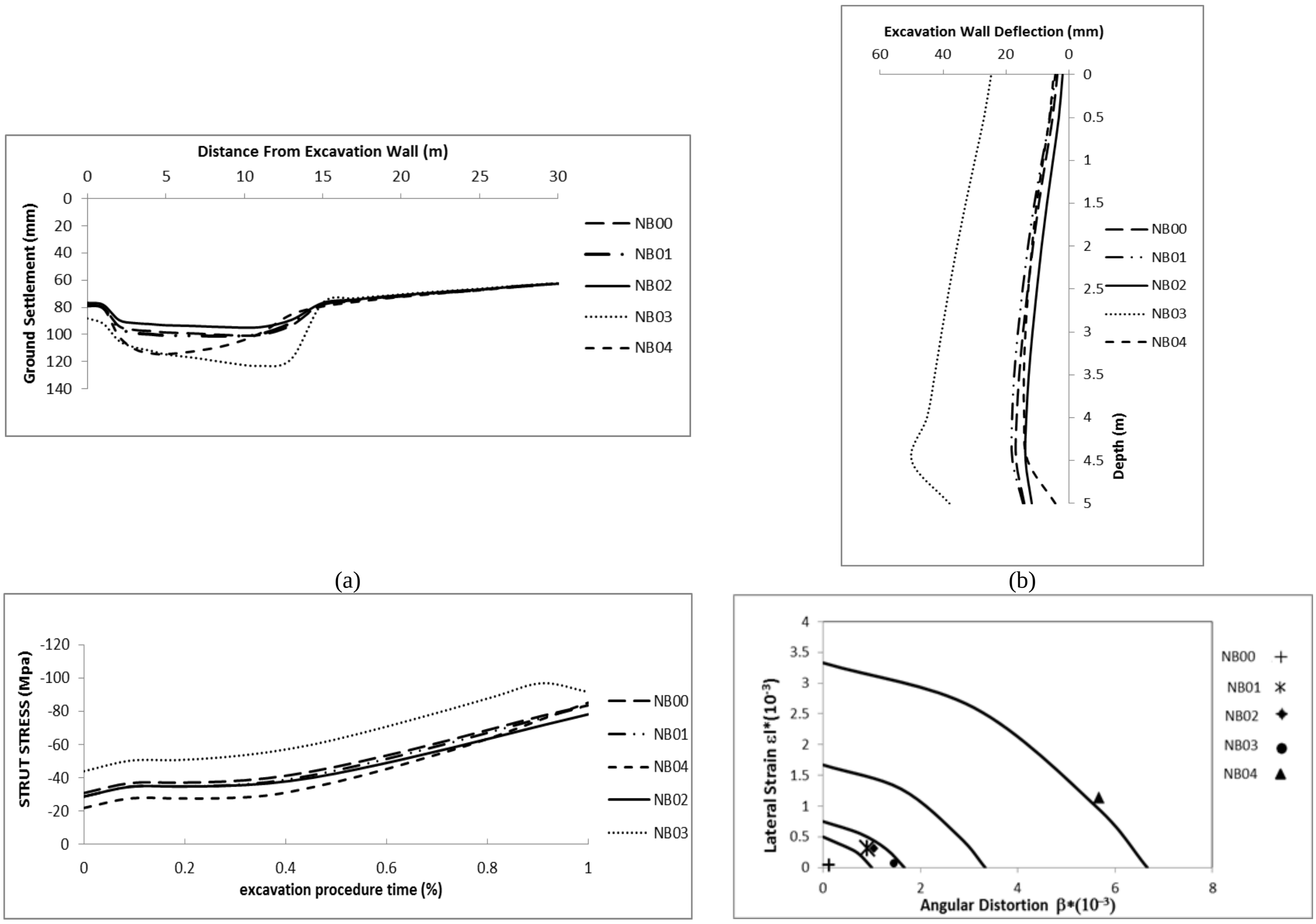


Fig. 11 (a) Ground surface settlement, (b) Deformation of excavation wall, (c) Strut stress during excavation procedure, (d) Deflection parameters of building in Boscardin and Cording diagram

Comparison between analysis NB01 and NB02 indicates the effect of opening ratio of adjacent building. It is obvious that the more the opening ratio, the less the ground and wall movements. This is mainly due to the fact that in the case of higher opening ratio, lower loads would be exerted to the ground. Fig. 11(c) shows that increase in opening ratio, decreases induced strut loads. It should be noted that increase in opening of structure can reduce overall stiffness of structure. Consequently as seen in Fig. 11(d) reduction of stiffness due to larger opening ratio, increases deflection parameters.

The effect of frictional contact interface is shown in the analysis NB03. It can be seen that, in general, frictional interface increases the ground and wall movements and strut loads. The type of interface affects the deflection parameters. In this case, due to frictional contact between structure and ground, ε_{lat} would reduce and damage level would increase.

Thus, it appears that a change in structure stiffness value significantly affects the structure deflection parameter, as compared with the other parameters of neighboring building.

Soil parameters

Table 6 lists the analyses performed to investigate the effect of soil parameters. The parameters that define these analyses are (i) Cohesion of soil (c) and, (ii) Stiffness of soil (E). To examine the effect of material properties, Tehran sediments were selected. A vast zone of Tehran is composed of coarse-grained cemented sediments and divided into four categories based on geological factors, and are identified as A, B, C and D alluvia. The A alluvium is the oldest and with strong cementation and D alluvium is the youngest with no cementation. Fakher et al [19] have been done the studies to determine geotechnical

[DOI: 10.22068/IJCE.13.1.1]

properties of Tehran. Their proposed values for Tehran sediments are shows in Table 7.

Table 6 Soil parametric analysis

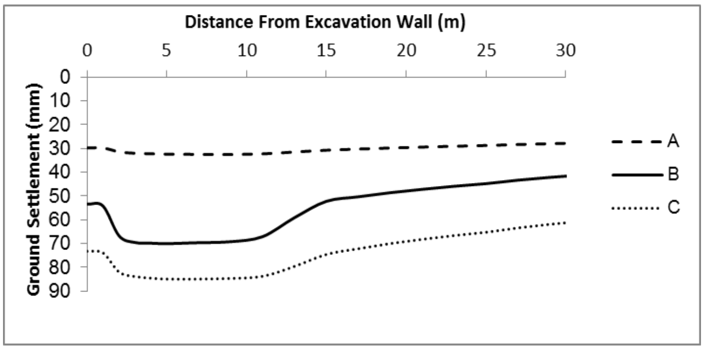
Number	Analysis	E (MPa)	c (KPa)	ϕ (degree)
1	A	200	90	40
2	B	100	20	15
3	C	50	30	30

Table 7 Geotechnical properties of Tehran sediments

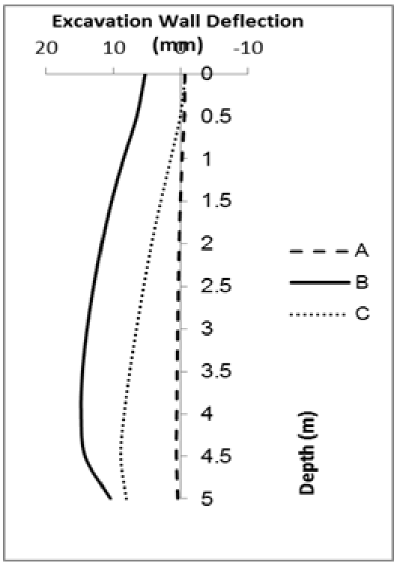
Deposit type	E (MPa)	c (KPa)	ϕ (degree)	γ (kg/m^3)
A	200	90	40	2200
B	100	20	15	1850
C	50	30	30	2000

Fig. 12 shows effect of soil parameters on soil displacements, building responses and the load carried by strut, and indicating that greater values of soil stiffness (*E*) result in smaller ground surface settlement. Comparison between results of analysis for soil B and C shows that increasing soil cohesion (*c*) and friction angle (ϕ), reduces the wall movements strongly. It can be seen the soil stiffness considerably affects the ground surface settlement while soil strength parameters (c and ϕ) significantly affect the horizontal wall deflections.

It can be seen in Fig. 12(c) for strut loads, indicating significant reduction in strut loads by increasing soil stiffness. But in soil B, strut loads increases due to increase in horizontal wall movement. Then it can be concluded that with decreasing soil cohesion (*c*) and friction angle (ϕ), strut loads increase significantly.



(a)



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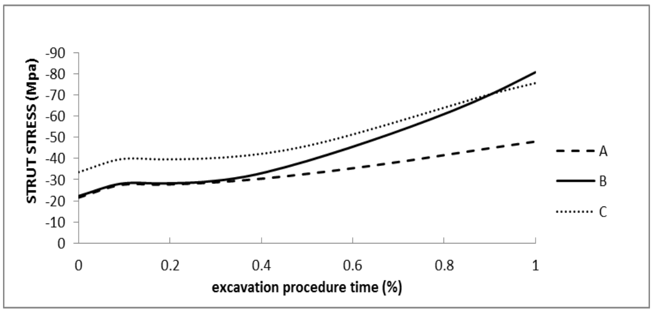
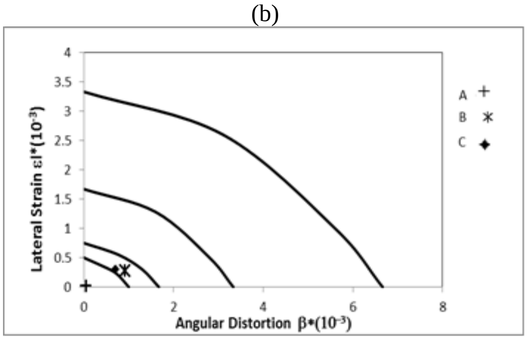


(c)



(d)

Fig. 12 (a) Ground surface settlement, (b) Deformation of excavation wall, (c) Strut stress during excavation procedure, (d) Deflection parameters of building in Boscardin and Cording diagram

Variation in damage measures of structure related to soil parameters are shown in Fig. 12(d). It can be seen that in the soils with large stiffness, smaller deflection parameters are obtained in adjacent buildings, and in the soils with small soil cohesion (*c*) and friction angle (ϕ), by increasing horizontal wall movement, ε_{lat} would be increased leading to a higher damage level.

Thus it can be seen excavation in deposit A produces smallest ground surface settlement and horizontal wall movement and produces minimum damage level in neighboring structures and consequently smallest inclined struts section.

Geometry of excavation

Dimensions of excavation in analyses are selected based on typical dimensions that are supported with inclined strut in the current state-of-the-practice. Inclined struts are not used in deep excavation, thus to examine the effect of the geometry, height of excavation is evaluated.

[DOI: 10.22068/IJCE.13.1.1]

The analyses in this set are listed in Table 8.

Table 8 Geometry of excavation analysis

Number	H (m)
1	2.5
2	5
3	7.5

Fig. 13 includes results of analysis at three different excavation depths.

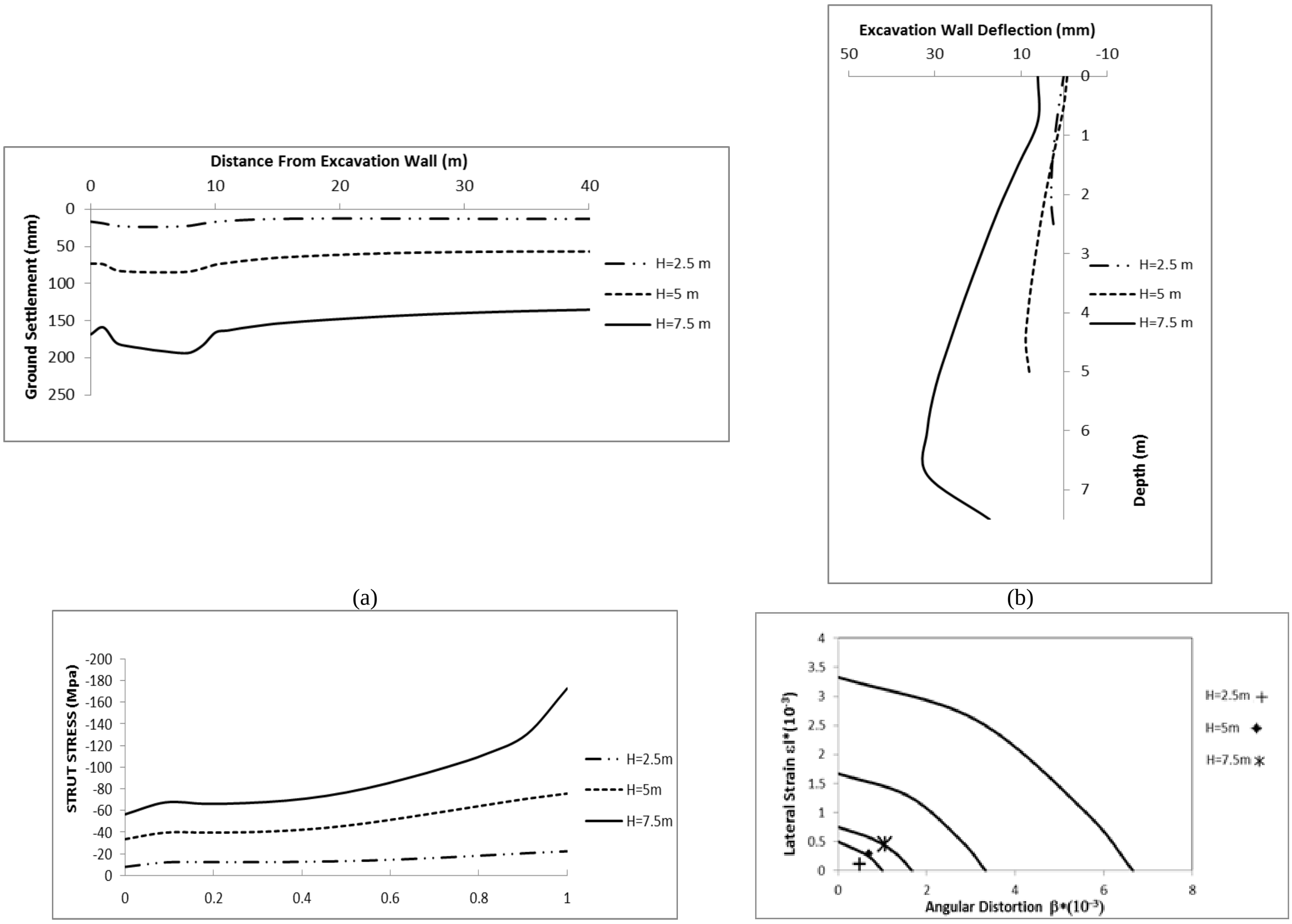


Fig. 13 (a) Ground surface settlement, (b) Deformation of excavation wall, (c) Strut stress during excavation procedure, (d) Deflection parameters of building in Boscardin and Cording diagram

Results show that ground and wall movements increase by increasing excavation depth strongly. This can also be seen in Fig. 13(c) for strut loads. The load carried by inclined strut increases with increasing excavation depth. Excavation depth can considerably affect the deflection parameters. In other words, higher excavation depth could lead to higher damage level.

It can be seen from Fig.13, increasing excavation depth by up to three orders of magnitude, resulted in an increase of the maximum ground surface settlement up to 9.5 times of magnitude, an increase of the maximum wall deflection up to 9 orders of magnitude, the increase of maximum strut stress up to 9 orders of magnitude and the increase of deflection parameters ε_{lat} and β, 6 and 3 times of magnitude respectively. It can be concluded the increase of the maximum ground surface settlement, maximum lateral wall deflection and maximum strut stress is approximately proportional to the square of the excavation depth increase. The increase of the ε_{lat} is approximately proportional to the twice increase of the excavation depth and The increase of the β is approximately proportional linearly to the excavation depth increase.

Excavation procedure

Four common configurations of excavation procedure that used in inclined strut support method are investigated in this set of analyses. In the first configuration, the struts are installed and connect the foundation of structure to the bottom of excavation at first; afterward, the excavation is performed. In the second configuration (Fig. 5), excavation at zone A are performed, then struts are connected to the foundation of structure and finally excavation at zone B are completed. Third configuration is

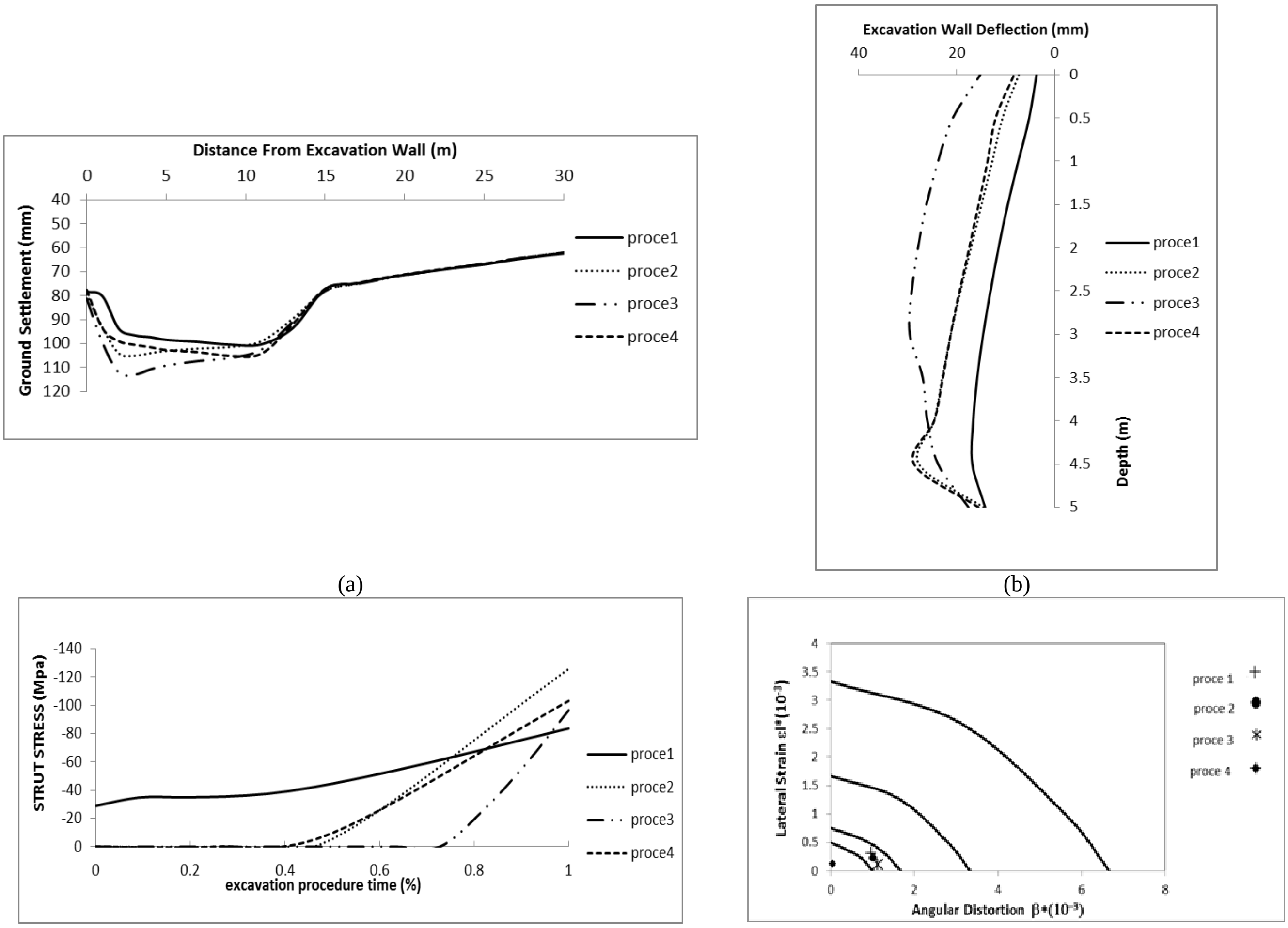
[DOI: 10.22068/IJCE.13.1.1]

composed of two stages. First is the execution of excavation, and second is the installation of struts. Forth procedure is similar to Fig. 5, but in this configuration struts connect the ceiling of first floor of structure to the bottom of excavation. The analyses in this set are listed in Table 9.

Fig. 14 shows the results of analyses. Procedure 1 in execution of excavation with inclined struts cause the smallest ground and wall movements compared to other procedures. Results of analysis for procedure 2 and 4 are similar in ground and wall movements and are greater than results of procedure 1. Execution of excavation with procedure 3 results in maximum ground and wall movements. This trend is also seen in strut loads.

Table 9 Excavation procedure analysis

Number	Procedure
1	proce1
2	proce2
3	proce3
4	proce4



(a) (b) (c) (d)

Fig. 14 (a) Ground surface settlement, (b) Deformation of excavation wall, (c) Strut stress during excavation procedure, (d) Deflection parameters of building in Boscardin and Cording diagram

It can be seen from Fig.14 (c) that the stress in a strut depends on the stage of strut installation and the position of strut installation to the neighboring building. The ultimate load carried by strut in procedure 1 is smallest. It can be due to that strut is installed before excavation initiation and smallest deflections occur. Procedure 3 causes greater strut load than procedure 1 and procedure 2 and 4 result in maximum ultimate strut load.

Comparison between procedures shows that the position of installation of strut seriously affects deflection parameters. Investigating the effect of configuration of excavation on adjacent building shows that procedure 4, in which strut is connected to the ceiling of first floor of structure, results in minimum deflection parameters and damage level. Other procedures cause approximately similar damage level though procedure 1 induces less angular distortion and procedure 3 induces maximum angular distortion.

It can be concluded that if inclined struts are connected to the building at lower level of building (e.g. to the foundation of building) the deformations of soil will be decreased and if inclined struts are connected to the upper level of building (ceiling of first floor of the structure), the deflections of adjacent structure will be decreased. Thus If the control of stability of soil is important, inclined strut should be connected to the foundation of adjacent building and if it is necessary to limit the damage of building to an acceptable level, inclined strut should be connected to the

[DOI: 10.22068/IJCE.13.1.1]

ceiling of first floor of the structure. However in general it should be noted that soil failure mode may be due to lack of bearing capacity of the foundation or instability of the excavation itself and this certainly affects the displacement field and performance of the excavation and adjacent buildings.

Inclined struts

Contribution of the strut stiffness is investigated per Table 10. For this purpose three different values are defined for strut stiffness. Strut stiffness is defined by its cross sectional area.

Table 10 Inclined strut parametric analysis

Number	Analysis	Strut	Moment of Inertia (cm^4)
1	ST00	Strut2	1.45×10^3
2	ST01	No	---
3	ST02	Strut1	0.33×10^3
4	ST03	Strut3	4.25×10^3

Obtained results are illustrated in Fig. 15. Comparison between analyses of excavation supported with inclined strut (ST00) and excavation without inclined strut (ST01) shows that excavation without inclined strut led to much greater ground and wall movements. Fig. 15(a) and (b) indicate softer strut increase ground and wall movements and stiffer strut decrease movements, although not significantly. From Fig. 15(c), it is clear that softer struts would carry greater loads compared with stiffer ones. The results also indicate that stiffness of the strut has a minor effect on the deflection parameters and the damage level of the building. Meanwhile, excavation without inclined strut would lead to larger deflection parameters and subsequently higher damage levels.

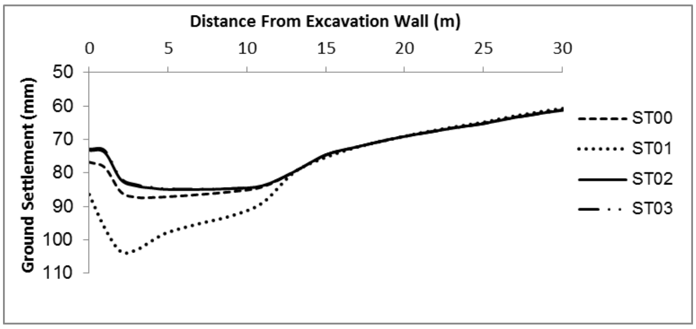
By comparing the numerical results between the cases with strut (ST00) and without strut (ST01), the effectiveness of strut can be evaluated. As shown in Figures, wall deflections and ground settlements in analysis with strut are considerably reduced, compared with the analysis results for the case without strut. Fig. 15(b) shows that the computed wall deflection in analysis with strut is much smaller than those without strut. It can be seen that the maximum wall deflection at the analysis with strut is reduced by 60%, by the installation of strut. Similarly, the maximum ground settlement at the analysis with strut is reduced by 20% by the installation of struts. Therefore, installation of struts can substantially reduce the lateral wall deflections and ground surface settlement.

Three different struts stiffness were considered to study the effect of strut stiffness on design factors.

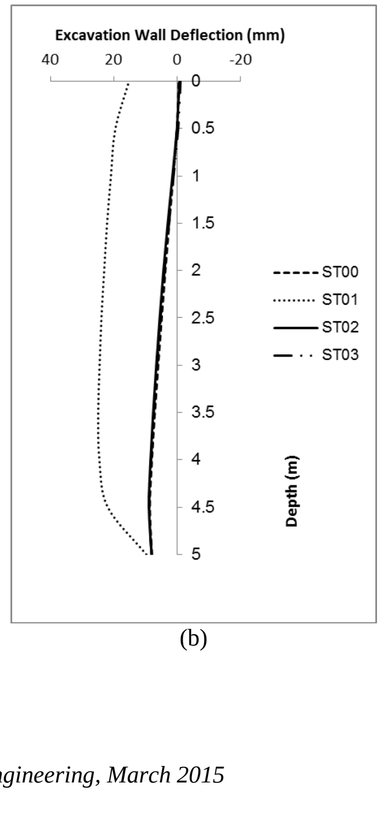
It is seen that when moment of inertia of strut varies from 0.33×10^3 to 4.25×10^3 cm^4 (about 12 orders of magnitude), the variations in the values of maximum ground surface settlement and maximum horizontal wall deflection are only 5 and 1% respectively. Thus, when other parameters are kept constant, for a particular soil there is no substantial change in displacements (either horizontal or vertical) for a higher value of strut stiffness.

Fig. 15 (c) shows the effect of strut stiffness on strut stresses. It can be seen that when moment of inertia of strut varies from 0.33×10^3 to 1.45×10^3 cm^4, the variations in maximum strut stress is about 85%, while when moment of inertia of strut varies from 1.45×10^3 to 4.25×10^3 cm^4, the variations in maximum strut stress is about 20%. It is concluded that with the increment of strut stiffness, the strut stress also decreased to a specific stiffness value with moment of inertia of strut of 4.25×10^3 cm^4, after which it became constant.

Thus, it appears that the optimum value of strut stiffness (with moment of inertia of strut of 4.25×10^3 cm^4) can be determined beyond which no further changes in strut stress, soil deflections and deflection parameters of building are observed.



(a)



(b)

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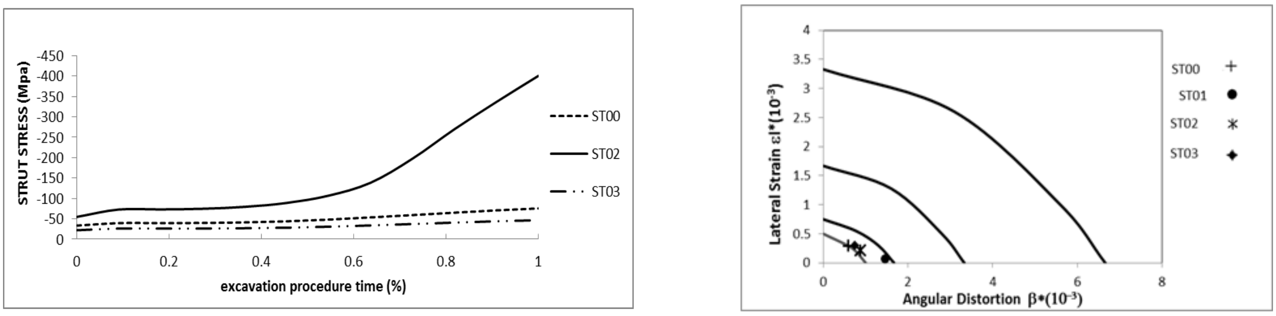

(c) (d)

Fig. 15 (a) Ground surface settlement, (b) Deformation of excavation wall, (c) Strut stress during excavation procedure, (d) Deflection parameters of building in Boscardin and Cording diagram

5. Overall Discussion

The governing parameters and possible mechanisms were previously presented and independently discussed; however, further overall discussion is required as follows:

5.1. Performance of building

In the analysis, the effect of various parameters on the performance of the building was investigated. The results showed that the stiffness of the adjacent building had a major effect on performance. If the stiffness of building is slight, it can increase the level of damage in response to an increase in the deflections in the building. Soil parameters can control the behavior of the building. Soil and building settlement are a function of soil stiffness; such that the larger the soil stiffness, the smaller the soil settlement and angular distortion. The cohesion of the soil can limit horizontal movement and control ε_{lat}. The effect of excavation depth on the horizontal deflection and settlement and, therefore, β and ε_{lat} are functions of excavation depth. Increasing the excavation depth increases the damage level. The contribution of the inclined struts on performance of the building is summarized in the following section. Most effective configuration of inclined strut installation occurs when the struts are connected to the ceiling of the first floor of the building.

5.2. Governing mechanism of inclined struts

The results of analysis show that inclined struts can (i) transfer a fraction of the adjacent building load to the bottom of the excavation and decrease ground surface settlement. (ii) They limit the excavation-induced horizontal wall deflection and (iii) prevent horizontal movement of the building toward the excavation. Decreasing settlement of the building can reduce the deflection parameters of the building and decrease damage to the building.

5.3. Suggested area of application of method

The parametric study showed that, in soils with low cohesion(c <25 kPa), the use of inclined struts can result in major damage to adjacent buildings, despite the use of other governing parameters. The settlement of foundations on cohesionless soils usually occurs because of the following two reasons; soil compressibility and lateral deformation of the foundation subsoil because of the tendency of soil to move away from underneath the foundation [20]. Studies also show that when excavation depth exceeds critical unsupported excavation depth($H_{cr}=4c/\gamma$), the use of inclined struts can result in major damage to adjacent buildings.

Results show that small stiffness of building, causes large deflection parameters and then damages will be in the severe category. Small stiffness of structure with respect to the soil stiffness, results in severe damage in building.

6. Conclusions

This study performed a series of 2D finite element parametric studies to investigate the effect of struts on deflections to adjacent buildings during excavations using the characteristics of the adjacent buildings, soil parameters, geometry of excavation, type of excavation and effect of strut installation as variables. The results can be used to approximate the reasonable design of struts. The FE model was validated using Rankine pressure and field measurements. Comparisons show that the model is capable of simulating many aspects of the behavior of excavations. The following conclusions resulted from the present research:

1) Of the variables examined in numerical analysis, the stiffness of the adjacent building, depth of excavation and soil stiffness were shown to have a significant effect on the performance of the building. Structural stiffness more significantly affected the structure deflection parameter of the neighboring building. Soil cohesion can strongly reduce horizontal wall deflection and limit damage to adjacent buildings.

2) Wall deflections and settlement are substantially reduced using inclined struts to adjacent buildings during excavation. The maximum lateral wall deflection decreased about 60% and the maximum ground surface settlement decreased by 20% after installation of the inclined struts. It was observed that soil stiffness considerably affects surface settlement and soil strength parameters (c and ϕ) significantly affect horizontal wall deflection.

[DOI: 10.22068/IJCE.13.1.1]

3) The use of inclined struts can be improved through the understanding the performance mechanisms by the professional community. Performance mechanisms for the inclined struts have been proposed using numerical analysis. It was concluded that inclined struts affect the performance of adjacent buildings through two mechanisms. One is that they transfer a fraction of the adjacent building load and reduce excavation-induced settlement. And inclined struts also limit the horizontal deformation of the excavation and the adjacent building. The decrease in horizontal displacement can have a significant impact on decreasing damage to neighboring building, as shown by Boscardin and Cording and Burland. This performance mechanism is advantageous for the excavations adjacent buildings, because ground deformation is minimized at the site of strut installation on adjacent building foundation.

4) When inclined struts are connected lower on a building at the foundation level, the mechanism (a) will dominate and the soil deformation will decrease. If the inclined struts are connected higher on a building near the ceiling of the first floor, the mechanism (b) will dominate and deflection of the adjacent structure will decrease. If the stability of the soil is important, the inclined strut should be connected to the foundation of the adjacent building. If it is necessary to limit damage of the building to an acceptable level, the inclined strut should be connected to the ceiling of the first floor of the structure.

5) It was found that design factors do not vary much when the strut stiffness exceeds a specific value, which in this study it corresponds to the strut moment of inertia of 4.25×10^3. As the increment of strut stiffness of the soil and structure deflection decrease up to this level of stiffness, the deformation will become constant or will decrease slightly.

6) Excavations in deposit A of Tehran sediment produced the smallest ground surface settlement and horizontal wall movement, minimum damage to neighboring structures and required minimal support.

7) An increase in maximum ground surface settlement, maximum lateral wall deflection and maximum strut stress is approximately proportional to the square of the increase in excavation depth. The increase in ε_{lat} is approximately proportional to the twice increase of the excavation depth and the increase in β is approximately linearly proportional to the increase in excavation depth.

8) The proposed support method is not recommended for cohesionless soils (c <25 kPa), for deep excavations ($H > H_{cr}$) and where the adjacent building is weak and there is low soil.

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[DOI: 10.22068/IJCE.13.1.1]