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A Numerical Investigation on the Performance of the Brick Stair Wall as a Supporting Structure by Considering Adjacent Building

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Abstract

Considering that one of the most important issues in urban excavations is the interaction between excavation and adjacent buildings, it is always crucial to study the behavior of the excavation system and its adjacent structures. Today, many methods are used to protect the stability of the excavations and to provide desired safety. One of these various methods is brick stair wall, which is used in some projects due to its characteristics such as its cost-effectiveness and proper function. Therefore, in this paper, the effect of using this method as the excavation supporting structure on the stability of the excavation wall and its role in reducing the deformation created in the wall and the surrounding ground, using Fast Lagrangian Analysis of Continua (FLAC), is discussed. The results show that the amount of deformation parameters of excavation and adjacent building constantly increase as the excavation depth and building weight increase or soil density decreases. In addition, the numerical simulations indicates that applied surcharge on the adjacent area of the stair wall (caused by the adjacent building weight) has the main effect on the damage criteria.

Keywords: *excavation, stair wall, numerical simulation, FLAC, adjacent building, brick wall*

1. Introduction

One of the most important geotechnical problems is the sustainability and protection of excavations. Based on statistical surveys in the past four years in Iran, the total accidents have accounted for an average of 37% in construction sites and more than 21% of total construction accidents in excavating and land preparation stages. Therefore, one of the important issues in constructing buildings is to provide proper stability during the destruction, excavation and execution of the supporting structure.

Gravity and semi-gravity walls are usually made of masonry materials (bricks and, mostly stone) with sandy mortar or simple (unarmed) concrete, and the stability of these walls against the lateral pressure is dependent on their weights. In some cases, these walls are armed with a number of bars, which causes the width of the wall to diminish to some extent, which defines semi-gravity retaining walls. One of the gravity wall types that does not require special equipment and highly skilled workforce, is Stair Wall. In excavations with low depth (up to about 4 meters) and to save money in supporting structures costs, traditional brick gravity walls (stair walls) are used. This method is based on the frictional force between the bricks (in the horizontal direction) and their weight force (in the vertical direction) (Prenay, 2014). Fig. 1 shows a brick stair wall section which has been used in one of the projects in Iran.

Masonry retaining walls are known as a traditional method used in different parts of the world, such as Asia, Africa, North America, Latin America, Europe and Australia. The stability of the masonry walls depends on several factors, including strength and specifications of materials, backfill conditions, blocks or bricks shapes and their layout. Many researchers have dealt with this, for example, the centrifuge model test (Yoshida, 2005), or actual size tests and experiments conducted by Yamamoto et al. (2010), who showed that materials strength and their cohesion are highly effective on the ultimate strength and deformation of the supporting wall. By using numerical modeling in the framework of continuum, Dewoolkar (2009) as well as Colas (2010) have achieved similar results. By numerical analysis and modeling of supporting walls and changing the wall geometric parameters, it was concluded that lower length-to-height ratio and height-to-width ratio of the wall, greatly cause to decrease the backfill settlement. In homogeneous masonry wall modeling, Mathieu *et al.* (2012) also investigated the effect of mortar properties on wall resistance and its possible damage under the lateral backfill pressure. They concluded that the mortar's strength and cohesion between the brick and mortar is considerably important, therefore, it is essential in homogenized modeling to equalize brick wall panel and mortar with a unit element having similar characteristics, and to carry out all the modeling based on this equivalent element. In this method, some failure modes such as the separation of brick from mortar or crack expansion in horizontal and vertical seams are ignored (Mathieu *et al.*, 2012).

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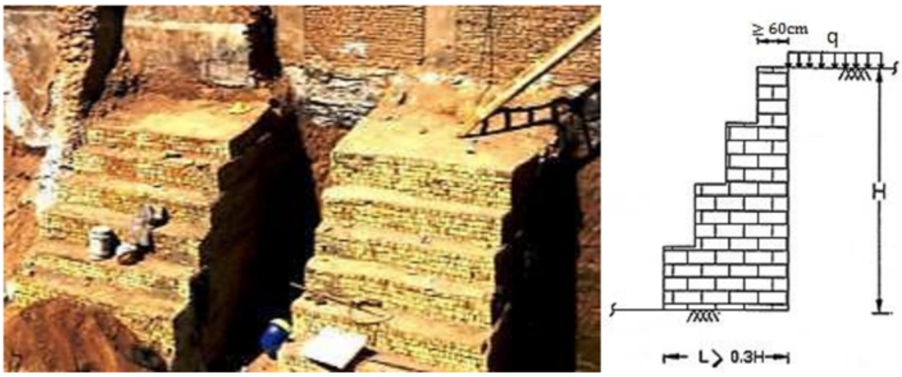

Fig. 1. Using the Stair Wall Method as Excavation Supporting Structure

One of the methods in numerical modelings is the Discrete Element Method (DEM) method, whose main advantage over the Finite Element Method (FEM) method is its ability to simulate large deformations, that is very complicated and difficult in the FEM method. Many researchers have investigated this issue, including Chen *et al.* (2014), Cai *et al*. (2014), and Wang and Yan (2012), all of which concluded the effectiveness of the finite difference method in modeling geotechnical issues.

Due to the importance of stability of the excavations and because of widespread use of masonry materials in construction, one of the excavation stabilization methods is brick stair wall which is a cost-effective and functional method. In this paper, in order to investigate the effect of the use of the brick stair walls on the excavation stability, first, the theory of this method is studied, and then, the numerical modeling is done using Finite Difference Method (FDM). Finally, results such as the displacement of the top of the stair wall, settlement of the excavation, the effect of changing soil properties, and so on are compared with existing damage criteria.

2. Damage Criteria

Generally, the criteria for structural damage are divided into two categories. The first category includes the criteria which are related to the resulted settlements and damages of the building under the vertical load (structure weight), without considering the effect of the adjacent excavation and horizontal strains created in the building. The second category includes criteria that are determined according to the excavation effects on adjacent buildings and horizontal strains and deformations. In this case, the values of allowed distortions and strains are more conservative and the damage degree is different from the first category.

In this paper, three of the most significant damage criteria are employed to be the reference for comparison with occurred displacements in models.

Boscardin and Cording (1989) illustrated the importance of direct horizontal extension in initiating damages. Fig. 2 illustrates the combination of angular distortion, defined in this case as the maximum change in slope along the "beam" or wall, and the horizontal strain. Fig. 2 was produced as a tool to assess structures with a length-to-height ratio (*l*/H) of 1.

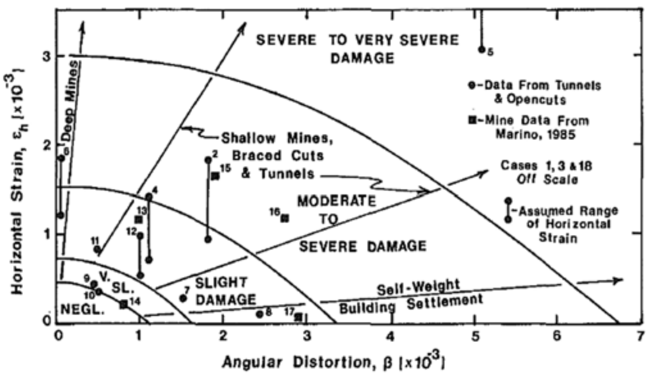

Fig. 2 Relationship between Damage Category, Angular Distortion and Horizontal Extention Strain (Boscardin and Cording, 1989)

Horizontal strain and angular distortion can be calculated using Eqs. (1) and (2), respectively (Boscardin and Cording, 1989):

$$\varepsilon_h = \frac{\rho_{h3} - \rho_{h2}}{L_{23}} \tag{1}$$

$$\beta = \frac{\begin{array}{c} maximun\ building\ settlement - \\ minimum\ building\ settlement \end{array}}{\begin{array}{c} distance\ between\ maximum\ and \\ minimum\ building\ settlement \end{array}} \tag{2}$$

where ε_h is horizontal strain, ρ_{h3} and ρ_{h2} are the horizontal displacement of the two adjacent columns toward the excavation which are shown in Fig. 3, L_{23} is the distance between the two adjacent columns and β is angular distortion (Boscardin and Cording, 1989).

Burland (1995) included lateral strain based on the work of Boscardin and Cording (1989) and adapted different values of critical strain to reflect different damage categories, as illustrated in Fig. 4. However, this approach was also limited to the case of *l*/H = 1 unless successive graphical constructions and interpretation are carried out. In Fig. 4, Δ is the maximum settlement, l is building length and $\frac{\Delta}{l}$ is considered as deflection ratio (Burland, 1995).

Day (1998) stated that in the criteria that are based on the width of the cracks created in the structure, factors such as invisible cracks, cracks caused by creep, shrinkage, etc., cannot

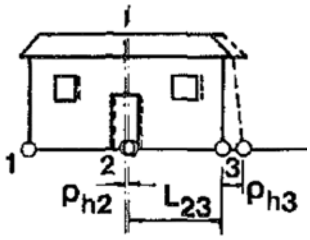

Fig. 3. Horizontal Displacement and Strain in the Adjacent Building (Boscardin and Cording, 1989)

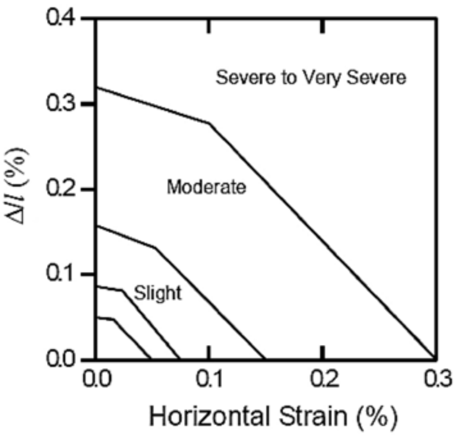

Fig. 4. Relationship of Damage Category to Deflection Ratio and Horizontal Tensile Strain for *l*/H = 1 (Burland, 1997)

Table 1. The Limits of the Differential Settlement, the Relative Rotation and Corresponding Degrees of Damage (Day, 1998)

Damage degree	Relative rotation limit	Differential settlement limit (cm)
0	Less than $\frac{1}{300}$	Less than 3
1	$\frac{1}{240}-\frac{1}{300}$	3–4
2	$\frac{1}{175}-\frac{1}{240}$	4–5
3	$\frac{1}{120}-\frac{1}{175}$	5–8
4	$\frac{1}{70}-\frac{1}{120}$	8–13
5	More than $\frac{1}{70}$	More than 13

be considered. Therefore, in order to increase the accuracy and validity of his criterion relative to other ones, he associated different degrees of damage with maximum relative rotation and maximum differential settlement, and presented in Table 1.

3. Research Method

In this study, the stair wall is modeled using Fast Lagrangian Analysis of Continua (FLAC). FLAC is a two-dimensional finite difference program for engineering calculations. This program can model the behavior of soil, stones, or other materials displaying different behaviors when approaching the failure state.

In this research, it is aimed to analyze the effect of using stair wall as excavation supporting system and to find its role in reducing the deformations created in the excavation wall and the surrounding ground. The modeling process includes creating the geometry of the model, assigning the specification of materials and boundaries, applying load and eventually analyzing the problem.

In order to simulate the body of the stair wall as well as the surrounding soil, the well-known linear elastic- perfectly plastic Mohr-Coulomb model has been utilized. The plastic part of this soil model is based on two important mechanical properties of soils, i.e., the internal friction angle and cohesion and the model is used for a variety of granular and cohesive soils. The Mohr-Coulomb criterion is expressed as Eq. (3):

$$\tau = c + \sigma_n tan\phi \tag{3}$$

where τ is the shear strength, σ_n is the normal stress, c is cohesion, and ϕ is the internal friction angle of the soil. In this study, non-associated follow rule is considered for the soil and the dilation angle (ψ) is considered as follows:

$$\psi = \phi - 30 \tag{4}$$

for the case of $\phi > 30^{\circ}$ and ψ is zero otherwise (Brinkgreve and Vermeer, 1998).

4. Verification

The Mohr-Coulomb model of FLAC is a model for continuous environments (Cundall, 2001) and the brick and mortar combination is a discontinuous environment. In order to employ this model for a brick wall, the performance accuracy of this model should be assured for the mentioned environment and parameters have to be calibrated. For this purpose, an experimental tests performed by Vermeltfoort *et al.* (1993) was selected to verify the numerical modeling. In the Vermeltfoort's test, a clay brick masonry wall with a central opening was loaded horizontally. The dimensions of the bricks used are 200 × 100 × 200 mm and the mortar thickness is 10 mm. The wall was subjected to a vertical constant pressure of 0.3 MPa from the top. Horizontal displacement (δ) is monotonically applied at the top layer that was clamped in a steel beam. The wall and its boundary conditions are observed in Fig. 5. Material properties derived from micro-test results are reported in Table 2 (Pandey and Meguro, 2004).

According to laboratory observations by Vermeltfoort et al. (1993), cracking in wall started from very early stages of loading initiating from loaded diagonal corners of opening. In Fig. 6, the observed cracking pattern in the experimental wall is shown (Vermeltfoort *et al.*, 1993). After modeling the wall in $FLAC^{2D}$ and performing the homogenization of the environment and calibration of the parameters, it was necessary to obtain the crack

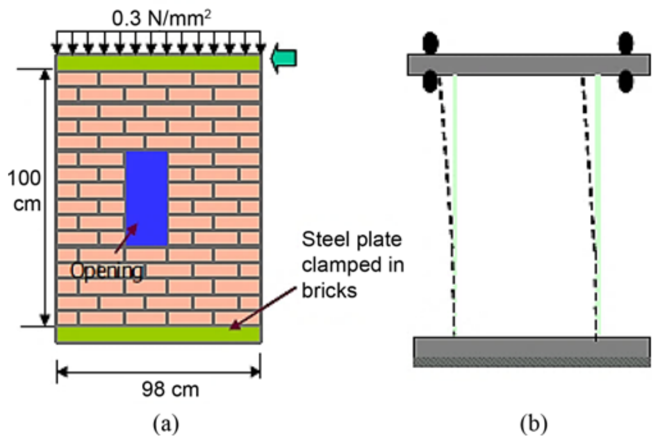

Fig. 5. Specifications of the Test Wall: (a) Geometric Characteristics of the Wall, (with) Schematic Boundary Conditions (Vermeltfoort *et al.*, 1993)

Table 2. Characteristics of Brick Wall Materials (Pandey and Meguro, 2004)

Parameter	Amount	Unit
Brick young modulus	16,700	MPa
Mortar young modulus	7,900	MPa
Brick tensile strength	2	MPa
Mortar joint tensile strength	0.25	MPa
Cohesion	0.35	MPa
Internal friction angle	36.5	Degree

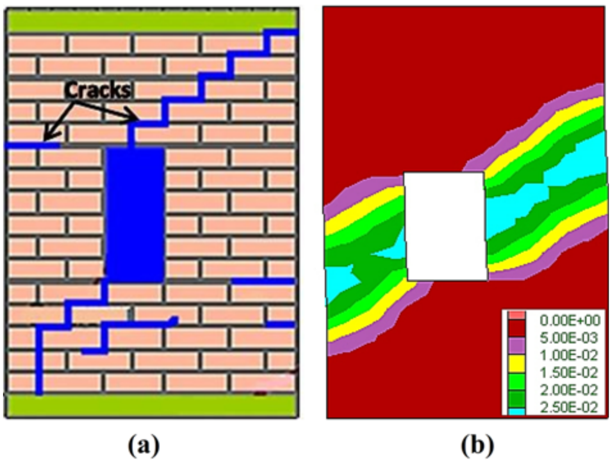

Fig. 6. Comparison of Damage Pattern in the Brick Wall: (a) Experimental Crack Patterns (Vermeltfoort *et al.*, 1993), (b) Maximum Shear Strain Increment Contours in the Numerical Analysis

patterns in the wall. With respect to contours, it can be seen that the maximum shear strain increment agrees well with the

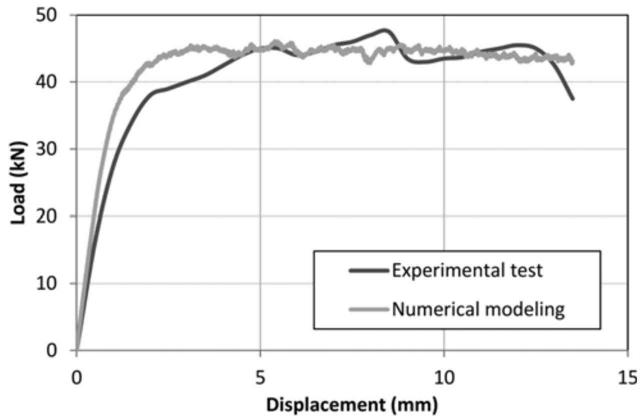

Fig. 7. Comparison of Load-displacement Behavior of Brick Walls in Experimental and Numerical Analysis

reported crack patterns in experimental wall.

According to the load-displacement diagram shown in Fig. 7, load-displacement behavior in experiment is well captured by numerical analysis.

5. Modeling Details

In this study, the effect of some changes on the excavation deformations are discussed which are listed below:

1) Increasing the excavation depth with the same soil characteristics and the same adjacent building floors in the modeling
2) Increasing the number of adjacent building floors with the same soil characteristics and the same excavation depth in the modeling
3) Changing the soil type from loose to dense sand with the same excavation depth and the same number of adjacent building floors in the modeling

A summary of the different conditions defined in the numerical modelings is presented in Table 3.

5.1 Numerical Models to Study the Effect of Excavation Depth

In order to investigate the effect of the excavation depth on the deformations created in the excavation wall and adjacent building foundation, the modeling is carried out at depths of two, four, six, eight, and 10 meters. In these modelings, the soil type and the adjacent building floors are assumed to be medium sand and four floors, respectively. The values of all the parameters used in these modelings as well as the geometry of all the models are shown in Table 4.

Table 3. The Conditions for Numerical Analysis

Type of model	Excavation depth (m)	Adjacent building floors	Soil type
Studying the effect of excavation depth	2 to 10	4	Medium sand
Studying the effect of the number of the adjacent building floors	4	2 to 10	Medium sand
Studying the effect of soil type	4	4	Loose to dense sand

Table 4. Parameters used in the Modeling to Study the Effect of Excavation Depth

Unit	Amount	Parameter	
kg/m^3	1,600	Special weight	Soil
MPa	20	Modulus of elasticity	
-	0.2	Poisson ratio	
Pa	1,000	Cohesion	
Pa	Zero	Tensile strength	
Degree	30	Internal friction angle	
Degree	Zero	Dilation angle	
Pa	40,000	Building weight tress	
m	12	Building length	Dimensions
m	1	The height of each stair of the stair wall	
m	1	The width of each stair of the stair wall	
GPa	18	Normal stiffness	Interaction
GPa	18	Shear stiffness	
Pa	1,000	Cohesion	
Degree	Zero	Dilation angle	
Degree	12	Internal friction angle	
kg/m^3	450	Unit weight	Stair wall
MPa	79	Modulus of elasticity	
-	0.15	Poisson ratio	
MPa	0.2	Cohesion	
MPa	2	Tensile strength	
Degree	10	Internal friction angle	
Degree	Zero	Dilation angle	

5.2 Numerical Models to Study the Effect of the Number of the Adjacent Building Floors

In order to study the effect of the number of the adjacent building floors on deformations created in the excavation wall and adjacent building foundation, several adjacent buildings are considered to have two, four, six, eight, and ten floors. In these numerical models, the soil type and the excavation depth are assumed to be the same as medium sand and four meters, respectively.

5.3 Numerical Models to Investigate the Effect of Soil Type

In order to study the effect of soil type on deformations created in the excavation wall and adjacent building foundation, three types of loose, medium and dense sand are considered in the modeling with the characteristics given in Table 5. In these models, the excavation depth and the number of adjacent building floors are assumed to be four meters and four floors, respectively.

Table 5. Parameters Considered for Different Soils in Modes to Study the Effect of Soil Type (Budhu, 2008)

Sandy soil type	Internal friction angle (degree)	Modulus of elasticity (MPa)	Poisson ratio	Specific weight (kg/m^3)
Loose	29	15	0.25	1,500
Average	33	30	0.3	1,550
Dense	37	60	0.35	1,700

6. Results

In this study, the results of modeling are divided into two main categories:

1) The effect of changing the conditions of excavation and surrounding area on the deformation characteristics of the excavations and
2) Finding the prohibited and allowed situations to use stair wall method as supporting structures in urban excavations, according to the available damage criteria.

The first category includes the results of changing excavation depths, applied surcharge by adjacent building, and soil type on the deformation parameters used in damage criteria in order to find the level of damage induced in adjacent building. The second category includes comparing the deformation parameters in each model to the mentioned damage criteria in this study and finding the situations in which, the damage level is acceptable.

It is also mentioned that in all the numerical modelings, no failure mechanism was observed in the body of the retaining walls. However, the wall movement could cause damage to the adjacent buildings because of mobilizing the shear strains in the soil beneath the adjacent building and back of the wall.

6.1 Effect of Increasing Excavation Depth

In this study, the effect of increasing the excavation depth on different characteristics is studied. First, the effect of changing the excavation depth on the vertical displacements in the whole model is shown in Fig. 8. As shown, by increasing the height of wall, the vertical displacement increases too. The amount of vertical displacement in models with the walls of 4, 6, 8 and 10 meters is 30, 60, 100 and 170 mm, respectively. The settlement-to-wall height ratio for these models are 0.75%, 1% , 1.25%, and 1.7% and increasing the height of the wall causes vertical

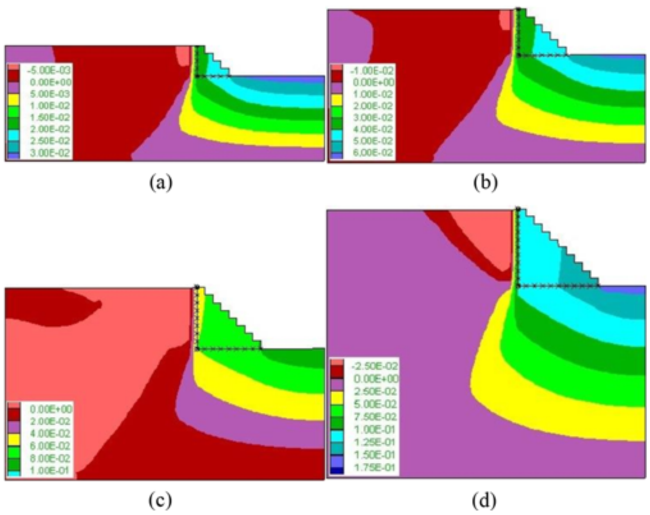

Fig. 8. Vertical Displacement Contours in Models with Depths of: (a) 4 Meters, (b) 6 Meters, (c) 8 Meters, (d) 10 Meters

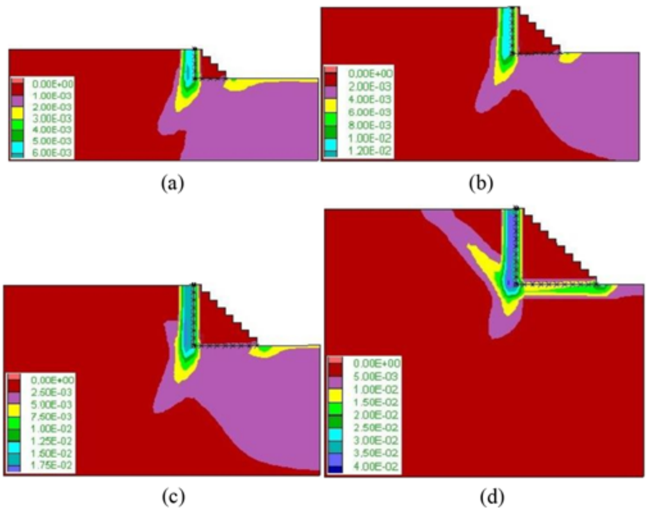

Fig. 9. Maximum Shear Strain Increment Contours in Models with Depths of: (a) 4 Meters, (b) 6 Meters, (c) 8 Meters, (d) 10 Meters

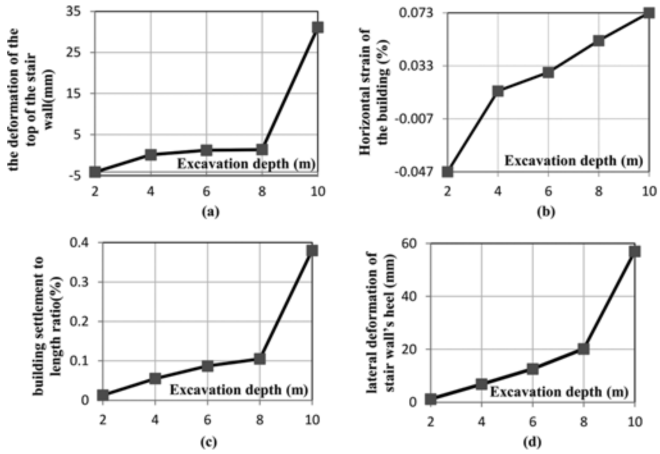

Fig. 10. The Effect of Increasing the Excavation Depth on: (a) the Deformation of the Top of the Stair Wall, (b) the Horizontal Strain of the Adjacent Building, (c) the Adjacent Building Maximum Settlement to Its Length Ratio, (d) the Lateral Deformation of Stair Wall's Heel

displacement at a higher rate.

The contours of maximum shear strain increment in the models with different depths are shown in Fig. 9. From Fig. 9 it is obtained that increasing the wall height causes to generate bigger shear strains. For the brick stair wall, the resultant force decreased suddenly, and its application point moved back toward the wall heel. These behaviors seem to be reasonable, considering a gradual increase in the overturning moment due to the horizontal inertia force of the wall and earth pressures, followed by the loss of bearing capacity near the toe of wall base at the loading time.

The effect of increasing the excavation depth on the deformation of the top of the stair wall, the horizontal strain of the adjacent building, the adjacent building maximum settlement to its length ratio and the lateral deformation of stair wall's heel, is shown in Fig. 10. In this figure, the number of adjacent building floors, the soil type and the distance between one-meter-wide stair walls are assumed to be four floors, medium sand and four meters respectively. According to Fig. 10(a), it can be seen that an increase in the excavation from two to eight meters, increases the deformation of the top of the stair wall. Up to a depth of about four meters, the deformation of the top of the stair wall is negative and towards the adjacent building and then it is positive and towards the excavation. From a depth of 8 to 10 meters, a dramatic increase in the wall deformation appears which is not acceptable according to mentioned damage criteria. According to Fig. 10(b), the horizontal strain created in the building constantly increases with increasing the excavation depth. Also, Fig. 10(c) shows that as the excavation depth goes up to eight meters, the adjacent building maximum settlement to its length ratio develops steadily, but from 8 to 10 meters, it witnesses a sharp jump, making it unacceptable according to mentioned damage criteria. Fig. 10(d) shows that the lateral deformation of stair wall's heel is always positive and towards the excavation. By increasing the depth from two to eight meters, this parameter has increased, but it then suddenly has rocketed.

6.2 The Effect of Increasing the Number of Adjacent Building Floors

The effect of increasing the number of adjacent building floors on the deformation of the top of the stair wall, the horizontal strain of the adjacent building, the adjacent building maximum settlement to its length ratio and the lateral deformation of stair wall's heel, is given in Fig. 11. In this figure, the excavation depth, the soil type and the distance between one-meter-wide stair walls are assumed to be four meters, medium sand and four meters, respectively. According to Fig. 11(a), it can be seen that

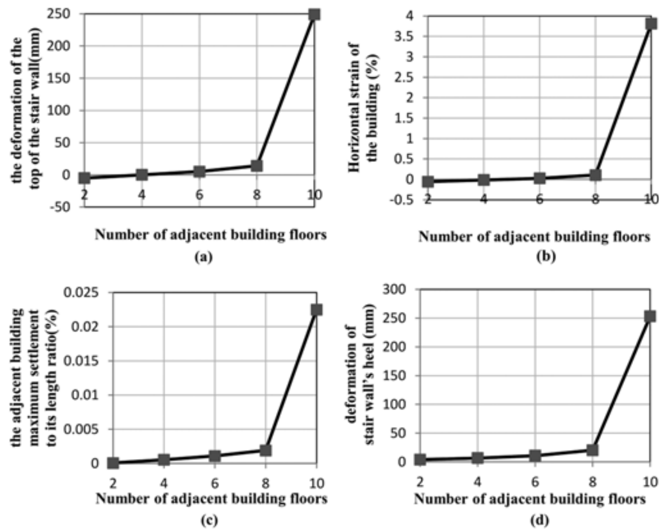

Fig. 11. The Effect of Increasing the Number of Adjacent Building Floors on: (a) the Deformation of the Top of the Stair Wall, (b) the Horizontal Strain of the Adjacent Building, (c) the Adjacent Building Maximum Settlement to Its Length Ratio, (d) the Lateral Deformation of Stair Wall's Heel

an increase in the number of adjacent building floors, from two to eight floors, and as a result, increasing the applied load on adjacent building foundation make the deformation of the top of the stair wall increases from 5 to 14 millimeters. However, this deformation escalates and makes this situation not allowable according to the damage criteria. Also, looking at Fig. 11(b), with increasing number of floors from two to eight floors, the horizontal strain created in the adjacent building increases and then, from 8 to 10 floors, the horizontal strain witnesses a sharp and unacceptable increase based on the mentioned damage criteria. Fig. 11(c) shows that by increasing the number of adjacent building floors from two to eight floors, the adjacent building maximum settlement to its length ratio increases from zero to 0.002 percent and making this number of floors more leads to a rapid jump which makes it unacceptable. Fig. 11(d) also shows that the lateral deformation of stair wall's heel has increased from about four millimeters to two centimeters with increasing loading due to the weight of the building and the number of floors from two to eight floors. Following this, by increasing the number of floors from 8 to 10 floors, this deformation meets a remarkable increase, making it unacceptable regarding damage criteria.

6.3 Effect of Soil Type Change

The effect of changing the soil type from loose to dense sand on the deformation of the top of the stair wall, the horizontal strain of the adjacent building, the adjacent building maximum settlement to its length ratio and the lateral deformation of stair wall's heel, is shown in Fig. 12. With regard to Fig. 12(a), it can be concluded that with an increase in the density of soil and its stiffness, the deformation of the top of the stair wall diminishes. Also, looking at Fig. 12(b), by increasing the soil stiffness, horizontal strain created in the adjacent building decreases. The reduction of the horizontal strain is due to the fact that, as the soil becomes stiffer, its horizontal deformation decreases. Also, Fig. 12(c) shows that with increasing the density and stiffness of soil,

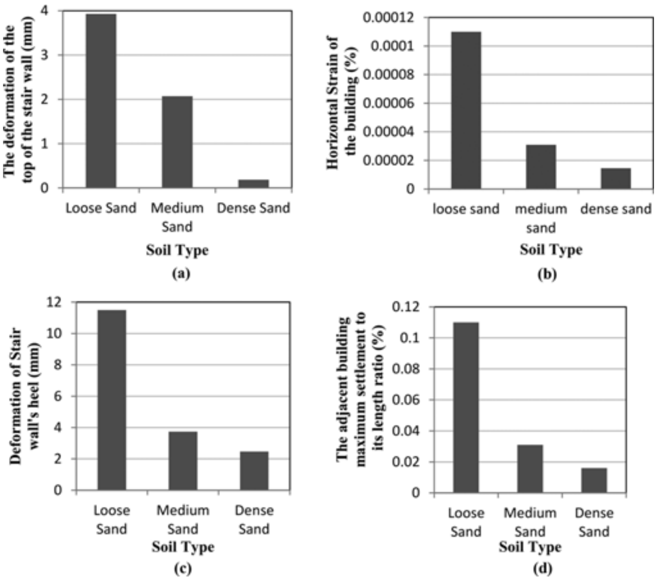

Fig. 12. Effect of Soil Type Change on: (a) the Deformation of the Top of the Stair Wall, (b) the Horizontal Strain of the Adjacent Building, (c) the Adjacent Building Maximum Settlement to Its Length Ratio, (d) the Lateral Deformation of Stair Wall's Heel

the adjacent building maximum settlement to its length ratio decreases from 0.11 to 0.016 percent. Fig. 12(d) also shows that the lateral deformation of stair wall's heel has been reduced by increasing the soil stiffness from 11.5 mm to 2.47 mm.

6.4 Comparing the Results of Modeling with Damage Criteria

In Table 6, the comparison of the results of the modelings with the criteria stated in the Section 2 is presented. In Burland's criterion (1995) and Boscardin and Cording's criterion (1989), the degree of damage to the adjacent building is obtained for

Table 6. Comparison of the Results of Modelings with the Criteria for the Structures under Their Weight and the Horizontal Strain due to Adjacent Excavation

Characteristics of Modelings			Burland's criterion (1995)	Boscardin and Cording's criterion (1989)	Day's criterion (1998)		
Constant Parameters	Variable parameter				Damage degree based on differential settlement	Damage degree based on angular distortion	Final damage degree
• Soil: Medium dense • No. of adjacent building floor: 4	Excavation depth (m)	4	Slight	Slight	0	0	0
		6	Moderate	Severe	0	0	0
		8	Moderate	Severe	0	1	1
		10	Out of range	Out of range	5	5	5
• Soil: medium dense • Excavation depth: 4 m	No. of adjacent building floors	2	V. slight	Negligible	0	0	0
		4	V. slight	V. slight	0	0	0
		6	Slight	V. slight	0	0	0
		8	Slight	V. slight	0	0	0
		10	Severe	Out of range	3	4	4
• No. of adjacent building floor: 4 • Excavation depth: 4 m	Sandy soil type	Loose	Slight	Slight	0	0	0
		Medium	V. slight	V. slight	0	0	0
		Dense	V. slight	Negligible	0	0	0

each model. In Day's criterion (1998), since the degree of damage is separately stated based on a differential settlement and the angular distortion of the building, the final degree of damage is considered conservatively. By comparing the results, it can be seen that there is generally a good agreement among the damage level predicted from different damage criteria. In other words, all the criteria can predict almost the same level of damage for the adjacent buildings. However, it should be mentioned that the Day's criterion gives less conservative result with respect to the other two criteria in the cases where the excavation depth is not so big. Based on the results comparison, it can also found out that the increase in the number of building floors abruptly influences on the damage criteria; the damage level of the adjacent building is very slight or slight if there are 8 floors; however, the criteria indicate that the building with 10 floors would collapse. Finally, the numerical results indicate that soil degree of compaction is not critical and it does not have influence on the predicted damage level.

7. Conclusions

The brick stair wall method has various considerable advantages, making it worthwhile to be considered in studies. The advantages include its economic efficiency, no need to employ very skilled human resource, no need to utilize special equipment, availability of required material in most of the construction sites and uncomplicated designing method. Hence, it is recommended to use this method in conditions that it is applicable, to save money, time and energy.

In this study, the performance of the brick stair wall as excavation supporting structure was evaluated by modeling this wall in different conditions (different excavation depth, different adjacent building weights and different soil types). Then, in order to determine the prohibited and allowed situations where it is appropriate to use stair wall as the excavation supporting system, the deformations resulted in the excavation was compared to damage criteria mentioned in Section 2. Conclusions are as follows:

1. In situations with medium to dense soil, the maximum excavation depth of four meters and the maximum distance of four meters between one-meter-wide stair walls, there is no ban on the use of the brick stair wall to protect the excavation if the adjacent building has up to four floors, due to the satisfaction of the damage criteria and being in slight damage range.
2. In situations with medium to dense soil, the maximum excavation depth of four meters and the maximum distance of four meters between one-meter-wide stair walls, stair wall should be prevented strongly to be used as the excavation supporting system if the adjacent building has more than six floors.
3. In situations with medium to dense soil, the maximum distance of four meters between one-meter-wide stair walls and the maximum number of adjacent building floor of four floors, for excavation depth up to six meters, stair wall is a suitable method for the stabilization of the excavation wall and for the depths over six meters, the use of this method is prohibited.
4. By increasing the excavation depth, the deformation of the top and the heel of the stair wall, the horizontal strain created in the adjacent building, and the adjacent building maximum settlement to its length ratio, constantly increase.
5. For low depths (up to four meters in the mentioned conditions), the top of the stair wall moves towards the adjacent building, instead of moving towards the excavation, and then, with increasing excavation depth, the movement is towards the excavation.
6. In all excavation depths, the movement of the stair wall's heel is towards the excavation.
7. By increasing the number of floors of adjacent building, the deformation of the top and the heel of the stair wall, the horizontal strain created in the adjacent building and the adjacent building maximum settlement to its length ratio, increases.
8. With a growth in the density and the stiffness of soil, the deformation of top and heel of the stair wall, the horizontal strain created in the adjacent building and the adjacent building maximum settlement to its length ratio, decreases.
9. The numerical results indicate that soil degree of compaction is not critical and it does not have influence on the predicted damage level.
10. Based on the numerical simulations, generally, there is generally a good agreement among the damage level predicted from different damage criteria. Among them, the Day's criterion gives less conservative result with respect to the other two criteria in the cases where the excavation depth is not so big.

According to the numerical simulations and comparing the results, it can be concluded that applied surcharge on the adjacent area of the stair wall (caused by the adjacent building weight) has the main effect on the damage criteria.

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