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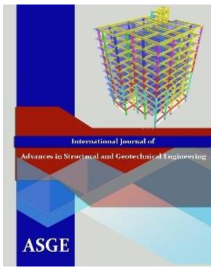

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Seismic Stability Evaluation Based on the Design Safety Limit of R.C. Building Frames Close to Slope

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ABSTRACT

This paper reports the application of different mid-rise moment-resistant building frame adjacent to an excavation area and knowing the performance levels to describe the state of structures after being subjected to a certain hazard level. Three types of mid-rise moment-resisting building frames, including 6-storey, 9-storey and 12-storey buildings, are selected. Building frame is constructed on a sand soil with layers of different density, representing soil class c, according to the Egyptian code practice. Different excavation depths, including 4m, 8m, and 12 m, are employed in the numerical modeling using finite difference software FLAC 2D. The above mentioned frame has been analyzed under two different boundary conditions: (i) flexible base (considering soil – structure interaction) without excavation and (ii) flexible base (considering soil-structure interaction) adjacent to excavation area. Elastic dynamic analyses under the influence of earthquake records for the three excavation depths previously mentioned are conducted. The results of the maximum lateral deflections and the inter-story drifts are used to determine the safe distance between the building frame and an excavation area. The results show that the increase in the excavation depth, structure height, and the decrease in the distance between the building and the excavation dramatically shift the pre-designed limit state of the structure from the life safety limit state to the collapse state under an anticipated earthquake action.

Keywords: Structure Interaction, Slope Elastic dynamic analyses, Mid-rise moment resisting building frames, Seismic analysis

INTRODUCTION

Many of the buildings are designed on fixed - base (no soil interaction) in the case of studying earthquakes loading, but the soil characteristics and the site's topography have an important role to determine the behavior of the building and the method of collapse. Many buildings collapse during earthquakes without the failure of the structural elements as a result of the collapse of the soil under the building, the overturning of the building, the impact of the type of soil, the construction of the building on a slope ground, or the escape of the soil under the building and other problems. Therefore, the researchers went on to study the effect of soil characteristics on the structure in the case of earthquakes. A fifteen story moment resisting building frame based on a soft clayey soil has been analyzed, and it is found that elastic and inelastic lateral deflections and inter-story drifts of flexible base model increase in comparison with fixed base model [1].

Other researches illustrated the influence of the excavation area on adjacent buildings. A multi-story building consisting of 6 to 12 floors rested on a flexible base is studied with the presence of excavation and with its absence. It has found that as the depth of the excavation, the distance from the edge of the excavation, or the height of the building increases, the lateral deflection and inter-story drift increases [2]

However, some researches suggested a number of methods to protect the buildings next to excavation areas. A study of a building with deep excavation was carried out. The sides of the excavation were supported by rigid retaining walls connected to prestressed piles. He calculated the settlement resulting from the static loads in the site and concluded the settlement of the building in the dynamic loads. As the depth of the excavation increases, the settlement increases [3]. A skirted foundation system was used adjacent to a sand slope and subjected to earthquake loading, which resulted in increasing the overall stability of the foundation and slope [4]. A laboratory study was conducted to determine the effect of the depth of the adjacent excavation and the movement of the lateral soil on the behavior of the adjacent strip footing [5]. Another laboratory study was conducted to improve the bearing capacity of the strip footing by using a row of piles or sheet pile [6]. Further studies have been made to enhance the bearing capacity through using structural skirts for a strip footing. It is indicated that as the skirts depth or the edge distance of footing from slope crest increases, the bearing capacity increases [7]. One of the safest lateral supports is the Pre-stressed tie back anchored diaphragm walls because they significantly reduce the maximum dynamic top wall lateral displacement [8].

It is clear from the previous researches that the presence of slopes or excavation next to the building reduces the bearing capacity of the soil or increases its settlement, especially in the case of earthquakes. Thus, the researchers turned to improve bearing capacity of the soil and reduce the settlement under buildings, either by making sheet piles or constructing the buildings on piles. Here, in view of the seismic performance limit states of RC buildings frames, a preliminary investigation is proposed to determine the safe distance between reinforced concrete building frames and excavation areas or slopes without supporting the soil sides.

Characteristics of Considered Building

Symmetric multistory buildings have been studied under the influence of an earthquake loading. These investigated models have been analyzed using SAP2000 "Structural Analysis Program" to determine the dimensions of the studied frames. Mid-rise buildings are located in an average height from 6 to 12 stories. In this study, the researcher has selected three models of structure (6-storey, 9-storey and 12-storey models) as per specifications, which are summarized in fig. 1 .

These dimensions are approximate to the usual construction practices in cities. Specified concrete compressive strength (f_c) and mass density (ρ) are assumed to be 320 kg/cm2 and 2500 kg/m3 respectively for the concrete structure utilized in this analysis and design. The modulus of elasticity of concrete (E) was calculated according to of ECP 2008 (Egyptian Standard for Concrete Structures) as follows: E =(14000√fc)

In this study, structural sections of the models were designed based on conventional elastic method. For this purpose, structural members of the S6, S9 and S12 models with story width 4m and story height 3m were simulated, analyzed and designed using SAP2000 V14 software.

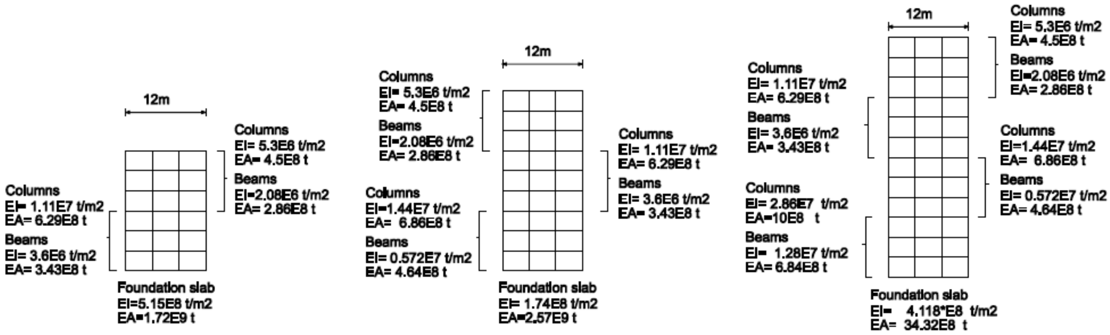

Figure 1. Structure models details

Elastic structural design

The building models are designed on the basis of elastic structure. The structural models are simulated in SAP2000 reflecting various properties of models S6 (6-storey), S9 (9-storey) and S12 (12-storey). Then, gravity loads including (dead) and (live) actions were determined and applied to the structural models, according to ECP 2008 (dead load, live load and other actions). The values of dead and live actions were determined as uniform distributed loads over the floors according to ECP 2008, considering the spacing of the frames being 4m as reported below:
Dead load (D) = 600 kg/m^2

Live load (L) = 200 kg/m^2

In addition, cracked sections for the reinforced concrete sections are taken into consideration by multiplying cracked section coefficients by stiffness values of the structural members (EI) according to ECP 2008. With this standard, cracked section coefficients are 0.35 for beams and 0.7 for columns.

After finalizing the dynamic analyses, concrete sections of three models (S6, S9 and S12) were designed according to ECP 2008 (Egyptian Standard for Concrete Structures). The following design load combinations were considered for concrete design of the structural members subjected to dead load (D), live load (L) and Earthquake (E) actions according to ECP 2008 (Egyptian Standard for Concrete Structures) Design Actions–General Principles:

Load combination 1 = 1.4D+1.6L

Load combination 2 = 1.5(D+ L)

Load combination 3 =1.4D+ 1.6L+1.6E

In the concrete design procedure, the capacity of each structural member is checked against the maximum factored axial force and bending moments obtained from each load combination considering capacity ratio giving an indication of the stress condition of a structural member with respect to the capacity of the member. In addition, shear capacity of the designed members is checked according to ECP 2008. After strength design of the structural sections, inter-story drifts of the models were checked to keep performance levels of the designed models in 'life safe' level by limiting the maximum inter-story drifts to less than 1.5% of the story height for each level. Inter-story drifts for each two adjacent stories can be determined according to their smallest allowed value from different codes.

Comparison between the codes in performance levels of structures

The calculation of the inter-story drift and the performance level of the buildings vary between the different codes. However, the method of calculating the inter-story drift in the elastic state depends on the difference in deflection between two adjacent stories multiplied by the reaction modifier divided by the height of the story without exceeding the permissible limit of safety.

Egyptian code practice (ECP 201, 2008)

$d_s=0.7Rd_e$
d_s is the maximum inelastic displacement, d_e is the maximum elastic displacement, R is the reduction factor (take 5.0)
$\text{drift} = \left[\left(\mathrm{d}_{(\mathrm{i+1})\mathrm{e}} - \mathrm{d}_{\mathrm{ie}}\right) \times (0.7R)\right]/\mathrm{h}$
The Egyptian Code did not mention limits for the performance states of RC buildings: the operational state, the life safety, the collapse prevention state [12].

Uniform Building Code (UBC 97)

$\Delta_M = 0.7R\Delta_s$
Δ_M is the maximum inelastic displacement, Δ_s is the maximum elastic displacement, R is the reduction factor (take 5.0)

$\text{drift} = \left[\left(d_{(i+1)e} - d_{ie}\right) \times (0.7R)\right]/h$

The life safety level is taken 2% in case the fundamental period is great than or equal to 0.7 second and is taken 2.5% in case the fundamental period is less than 0.7 second [13].

American Society of Civil Engineers, ASCE 7-10

$$\delta_x = \frac{C_d \delta_{xe}}{I_e}$$

δ_{xe} is the deflection determined by the elastic analysis , $C_d$is the deflection amplification factor , I_e is the Importance factor

$\text{drift} = \left[\left(\delta_{(i+1)e} - \delta_{ie}\right) \times (C_d/I_e)\right]/h$

The life safety level is taken 1.5% for buildings located in Risk Category three [14].

Australian Standards , AS1170.4

$$\text{drift} = \left[\left(d_{(i+1)+e} - d_{ie}\right) \times \left(\mu/S_p\right)\right]/h$$

where the structural ductility factor (μ) = 3.0 and the performance factor (Sp) = 0.67. $d_{(i+1)}e$ is the elastic deflection at the i + 1 level, d_{ie} is the elastic deflection at the i level factor and h is the storey height.

By comparing the different codes to calculate the inter-story drift and the performance level, it is found that the Australian code gives the least allowed value to the inter-story drift, which is 1.5% of the story height, according to the safety limit. Therefore, the inter-story drift will be compared according to the Australian code [15].

Soil–Structure System and Interface Elements

Soil structure interaction is a complex study as it is influenced by the alternate effects of soil and building. The FLAC2D V4.0 (Fast Lagrangian Analysis of Continua) program, which is used in this study, is a two dimensional program for engineering mechanics computations. The calculation is based on the explicit finite difference scheme to solve the full equations of motion using lumped grid point masses derived from the real density of surrounding zones [16]. Thus, FLAC2D models the soil-structure system and solves the governing equations for the complex geometries and boundary conditions. This program can simulate the behavior of different shapes of earth and building structures.

Beam structural elements are used to model the different components of RC building frames including beams, columns and foundation slabs. They are two-nodded and straight elements with six degrees of freedom per node comprising three translational and three rotational components. Soil medium beneath the structure is simulated using two-dimensional plane-strain grids. Quadrilateral elements are four-sided elements usually containing four nodes in a rectangular configuration.

The strip reinforced concrete foundation is 1m wide and 12m long. As, the selected model is two-dimensional, plane strain, the moment of inertia of the concrete raft foundation has been calculated by a 1 meter width.

The interface between the foundation and soil is modeled using linear spring system, with the interface shear strength defined by the Mohr–Coulomb failure criterion and is symbolized by shear (K_s) and normal (K_n) springs between two planes contacting each other (Figure 2). The relative interface movement depends on interface stiffness values in the normal and tangential directions. However, this assumption does not influence the numerical results as there is no large slip between the soil and foundation. Shear and Normal spring stiffness values for interface elements of the soil–structure model are 10 times the equivalent stiffness of the contacting zone [7],[16] for the isotropic soil medium as follows:

$$K_n = K_s = 10\left[\frac{\left(K + \frac{4}{3}G\right)}{\Delta Z_{min}}\right]$$

K and *G* are the bulk and shear moduli of the contacting zone, respectively, and ΔZ_{min} is the smallest width of an adjoining zone in the normal direction.

The effect of horizontal soil boundary distance variations on the seismic response of different structural models is experimentally studied. Two boundary distances of 10B and 5B, where B is the foundation width, are examined. The results showed that increasing the distance of the soil boundaries from 5B to 10B has a small effect (5% change) on the seismic response of the models, whereas it has a significant effect on saving time and cost of the numerical calculations [7, 1]. Thus, it is concluded that placing the soil boundaries at a distance equal to five times the width of the structure is appropriate while conducting numerical or physical modelling for seismic purposes. For lateral boundaries of the soil medium, quiet boundaries (viscous boundaries) are utilized in this study [10]. The proposed method applies independent dashpots in the normal and shear directions at the model boundaries. Moreover, in the developed soil–structure model, the boundary conditions at the sides of the model simulate the free-field motion that would exist in the absence of the structure. Free-field boundaries were simulated using a developed technique [11], which is used in FLAC2D. It should be noted that both absorbent (viscous) and free-field boundaries were modelled together (Figure 2). The reflection of the wave from the boundaries is prevented by the absorbent boundary conditions, and free-field boundary conditions allow the lateral deformation of the boundaries like what exists in the field in the absence of structure. The rigid boundary condition is the most suitable and realistic condition for modeling bedrock for dynamic soil–structure analysis. According to the previously mentioned studies, rigid bedrock boundary condition is used in the soil–structure numerical model in this study.

Properties of the Applied Soil

In this study, three layers of soil of different characteristics comprising one cohesion less were used. Characteristics of the adopted soils are listed in Table 1, and they are extracted from an example in FLAC. Furthermore, the authors assumed that the water level is below the bedrock level. Shear and Normal spring stiffness values for interface elements of the soil–structure model are shown in Table 2.

Table 1. Adopted Mohr–Coulomb soil parameters in the soil–structure model.

Soil type	ϕ (deg)	C (kPa)	G (t/m^2)	K (t/m^2)	ρ (kg/m3)	V
Soil type 1	40	4	2.35E4	5.09E4	2009	0.30
Soil type 2	35	2	6.30E3	1.36E4	1813	0.25
Soil type 3	30	2	6.30E3	1.36E4	1715	0.25

ϕ, internal friction angle; C cohesion; G, shear modulus; K, bulk modulus; ρ soil density; v Poisson's ratio.

Table 2. Utilized soil interface parameters.

Soil type	K_n(t/m^2/m)	K_s(t/m^2/m)
Soil type 3	2.2E5	2. 2E5

Numerical Study

Elastic analyses were carried out for structural models S6 (6-storey), S9 (9-storey) and S12 (12-storey) with characteristics described in Fig. 1 in conjunction with the three soil types mentioned before for two different cases: (i) flexible base (considering soil-structure interaction) without excavation and (ii) flexible base (considering soil-structure interaction) adjacent to excavation area in Fig. 2.

To perform a comprehensive investigation on the seismic response of structural models, the matched El Centro time history was studied for medium-rise buildings constructed next to excavated areas to see the linear dynamic behavior of buildings. The acceleration time history must be well-matched with the design response spectra at the intended site. The selected real ground motion records (PEER 2013) are scaled to match the proposed elastic design spectrum

(ECP 2008) using Seismo Match software by a time domain scaling method [19], as shown in Fig. 3. For the response-history analysis, the code, the origin and the matched ground motion spectra are shown in Fig. 4. The authors used the base line correction to correct the acceleration record from the site as a time history. The FLAC model may display continuing velocity or residual displacements after the motion has finished. This arises from the fact that the integral of the complete time history may not be zero [16].

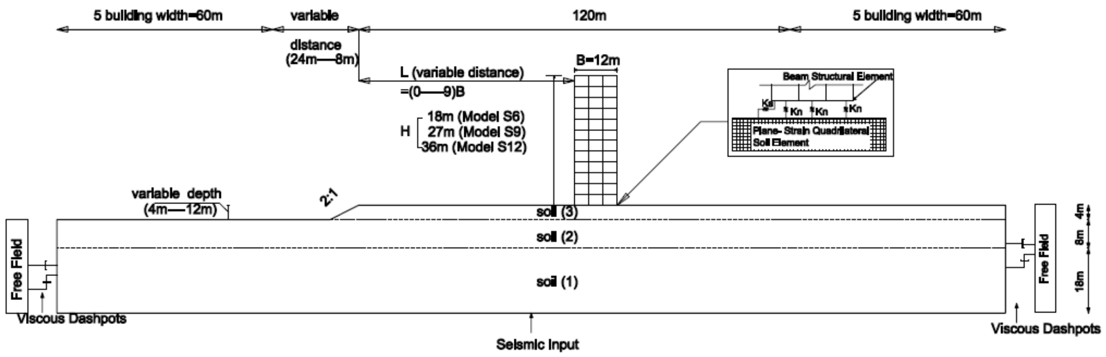

Figure 2. Simulating lateral boundary conditions for soil–structure model next to an excavation area

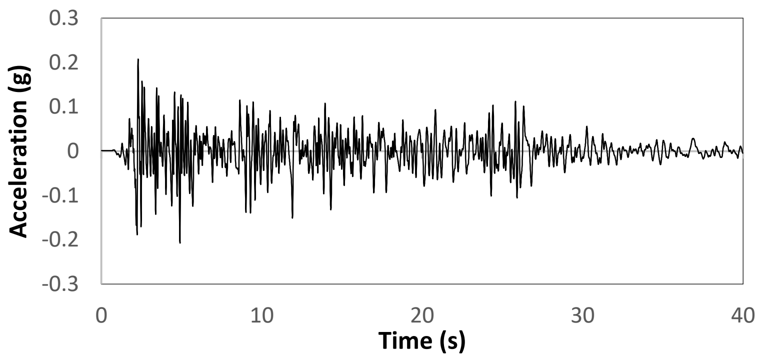

Figure 3. The matched acceleration record of El Centro earthquake (1940).

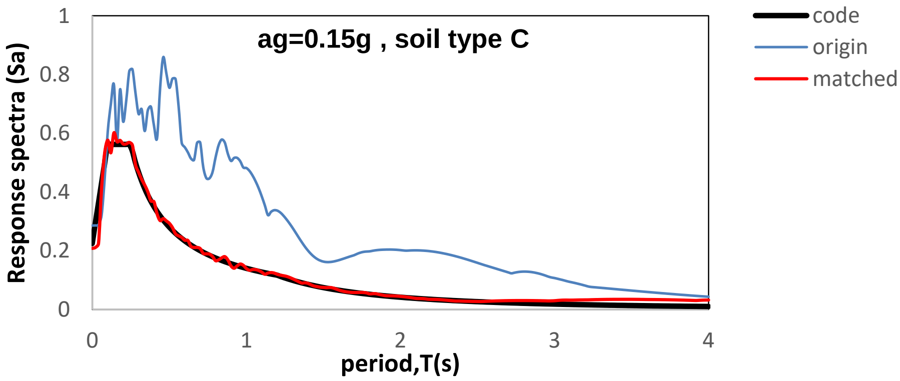

Figure 4. Response spectra of the earthquake along with the design response spectrum (ECP 2008)

In this study, the horizontal distance of the soil lateral boundaries without excavation area is assumed to be 132m (ten times the width of the structure, which is 12 m), and the bedrock depth is 30m divided to three layers. The top layer is soil type 1 of 4m depth. The following layer is soil type 2 of 8m depth, and the last layer at the bottom is soil type 3 of 18m depth. In the presence of an excavation area adjacent to a building, the horizontal distance of the soil lateral boundaries was simulated as shown in Fig. 2.

Results and Discussions

The maximum lateral displacements of the stories and the inter-story drift were calculated in the case of adjacent excavation areas and in the case of its absence. The study was applied to a concrete frame with different heights (6, 9, and 12 stories) and different depths for adjacent excavation (4, 8, and 12 m). The results of the elastic analyses including lateral deflections were derived from FLAC2D history records. The flexible base models rest on soil type (c) according to ECP 2008 and on a soil with different excavation depth of 4 to12 m. Average values of the maximum elastic lateral deflections under the influence of El Centro earthquake records were determined. The discussion of the results of the frames were analyzed in the elastic stage.

Figs. 5 and 6 show the X-displacement contours of the S9 model. The excavation distance was 12m, and the distances from the frame to the slope crest were equal to 7B and 1B, respectively. The soil escaped under the building along the direction of excavation with the settlement of the building foundation. This is usually associated with a considerable decrease in the bearing capacity of the soil beneath the building during earthquakes. This result ultimately leads to a significant increase in lateral deformation and an excessive increase in the inter-story displacement, which will be discussed in the following sections.

Lateral Deflections and Inter-Story Drifts

When buildings are located near excavated areas, the bearing capacity of the soil decreases under the building due to its escape in the direction of excavation during earthquakes. Figures 7, 8 and 9 show that the maximum lateral deflection increases as the depth of the adjacent excavation increases or as the frame of the excavation gets closer. The value of the maximum lateral deflection of the frame with excavation will be equal to its value in the absence of excavation.
Therefore, in case the mid-rise moment-resisting building frames are at greater distances than the previously mentioned, the frame will be within the range of the life safety zone, provided that the soil classification (c) is according to ECP 2008. If the distance between the frame and the edge of the excavation is less than the cases mentioned above, the building will get into the stage of collapse during the seismic action, so it must be secured.

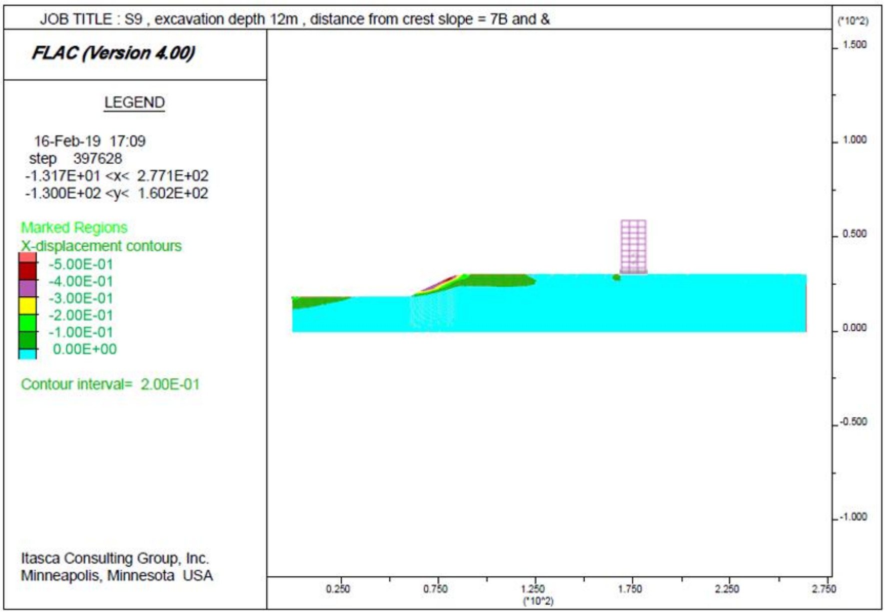

Figure 5. X-displacement contours for model S9 with excavation depth 12m and distance from frame to slope crest 7B

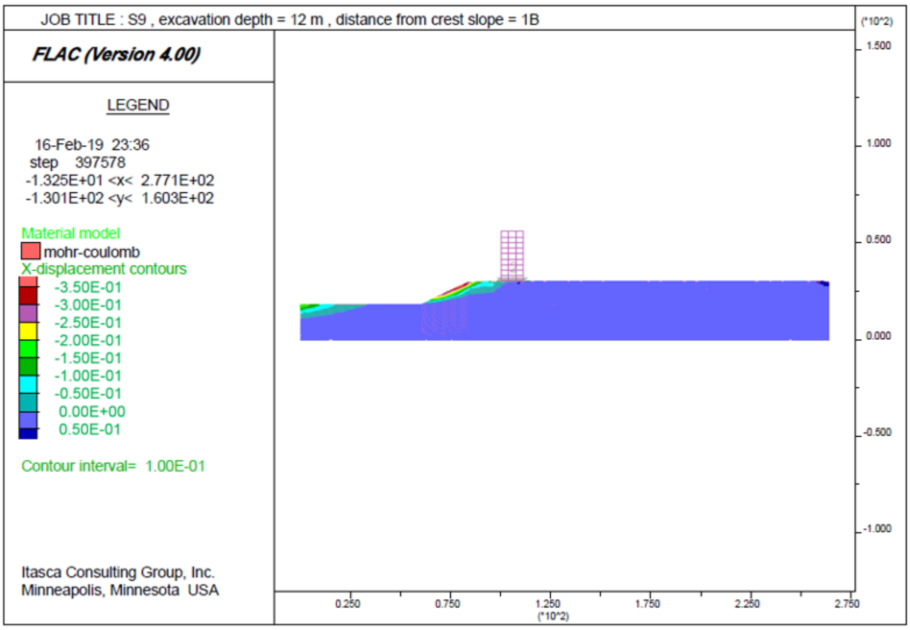

Figure 6. X-displacement contours for model S9 with excavation depth 12m and .distance from frame to slope crest 1B

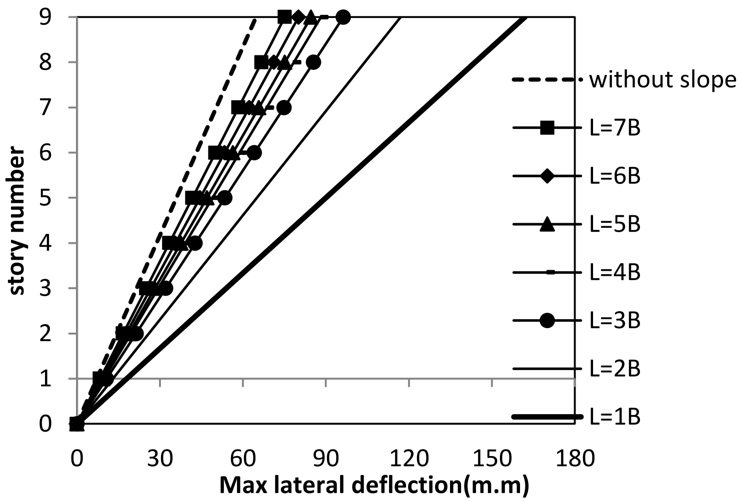

Figure 7. Max lateral deflection for model S9 with excavation depth 12m

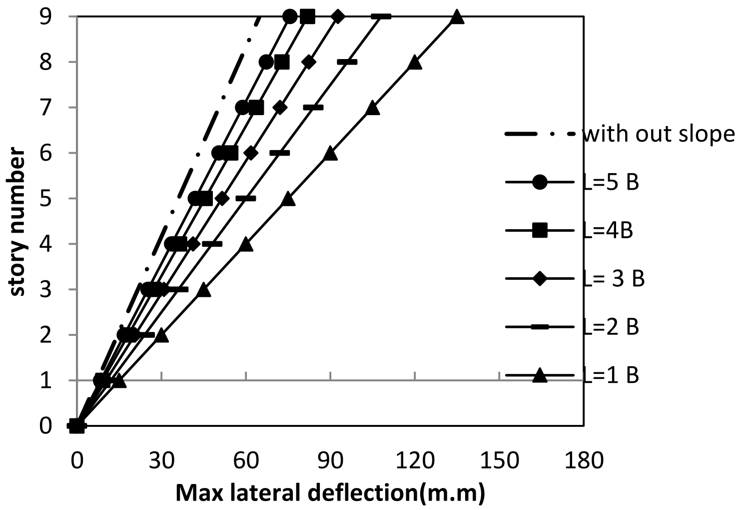

Figure 8. Max lateral deflection for model S9 with excavation depth 8m

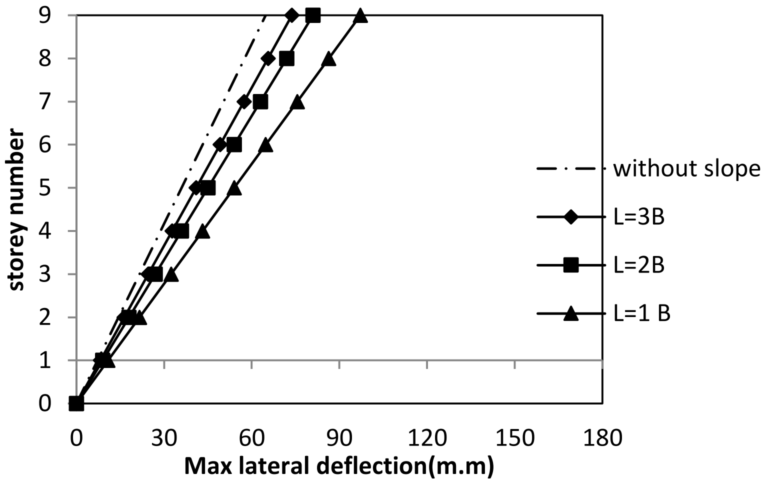

Figure 9. Max lateral deflection for model S9 with excavation depth 4m

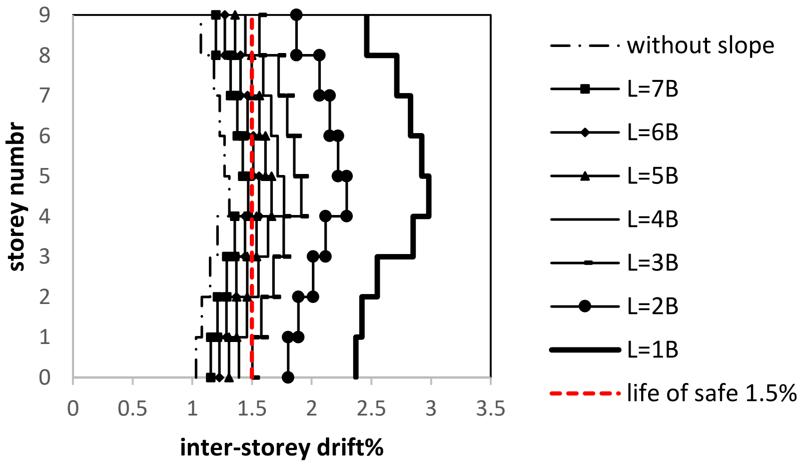

Figure 10. Elastic inter-story drifts for model S9 with excavation depth 12m.

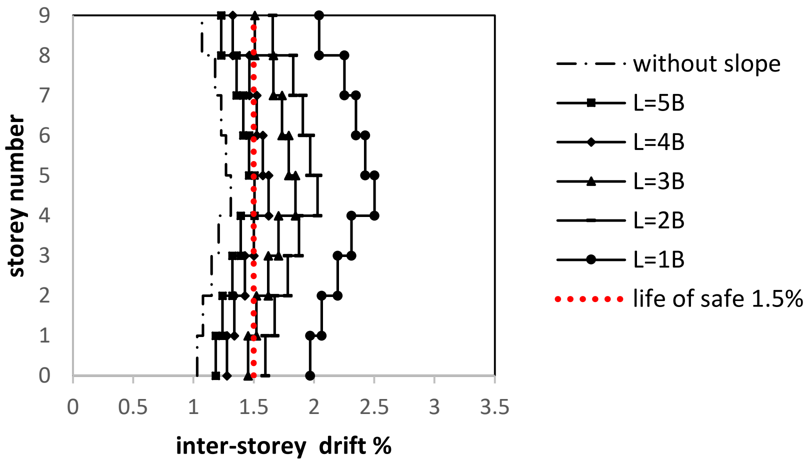

Figure 11. Elastic inter-story drifts for model S9 with excavation depth 8m.

In general, as the distance between the frame and the edge of the drilling decreases, the inter-story drift increases, accompanied by a change in the performance level of the structures from life safe to near collapse or total collapse. Moreover, the higher the frame at the same depth of the adjacent excavation, the more distance the frame will need to become in the safe life limit. By

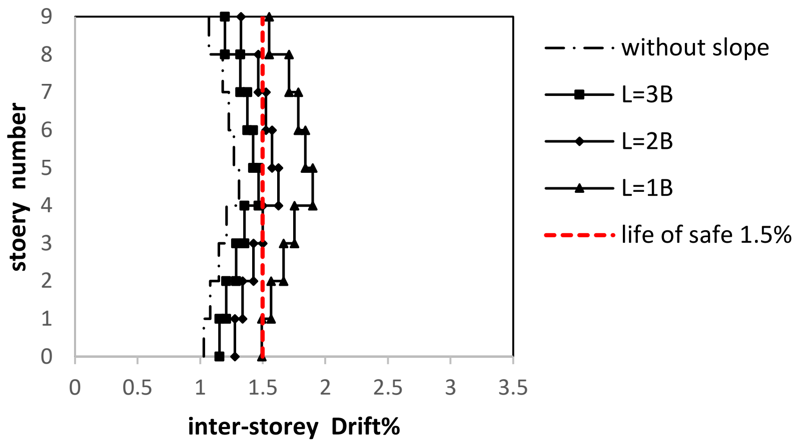

Figure 12. Elastic inter-story drifts for model S9 with excavation depth 4m.

studying the different heights of the 6, 9 and 12 story frame and by comparing the Figs. 7, 8 and 9, it evident that the S12 frame requires a minimum distance of 3B to 7B, the S9 frame requires a minimum of 2B to 6B, and the S6 frame requires a minimum distance of 1B to 4B according to the different depths of the adjacent excavation of the building (4, 8 and 12 meters). In these limits, the building will be in the safe stage as shown in Figure 13.

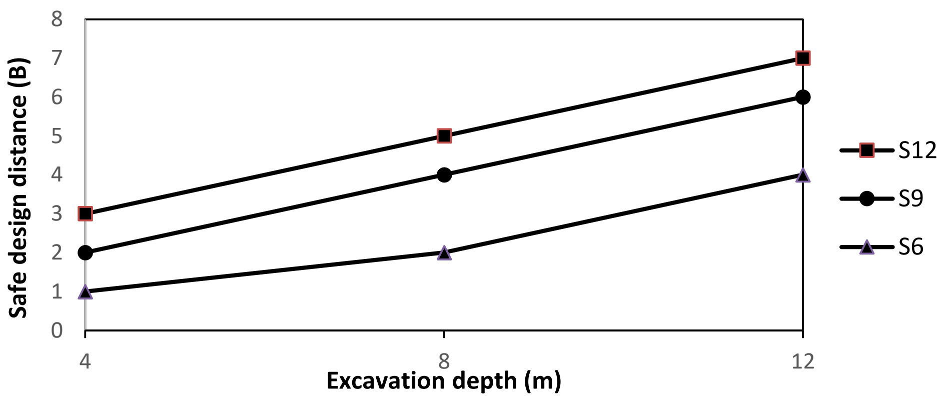

Figure 13. Safe design distance from frame to excavation edge

Conclusion

This research illustrates the effect of the excavated areas on the adjacent buildings in the case of earthquakes and the importance of considering the impact of the soil on characteristics and typography of the buildings. We have modeled the buildings in the form of a multi-story concrete frame based on the soil. With changing the height of the building, the depth of the drilling, and the distance of the building away from the excavation, the researcher has found the following:

1- In the case of changing the depth of the drilling adjacent to the nine-story floor from 4 to 12 meters, the safe distance changes from 2B to 5B.
2- In the case of increasing the height of the frame adjacent to a drilling area of 4 meters depth from 6 to 12 floors, the safe distance change from 1B to 4B.
3- If the building is located at distances less than the ones mentioned above, the effect of the soil structure interaction should be considered because in this case the building increases the inter-story drift, and the building may become not compatible with the safety limits. Therefore, different means must be taken to secure the buildings, whether by constructing sheet piles near to the excavation area or by constructing the building itself on piles.

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