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Numerical Simulation of Building Behavior Adjacent to Soil Nailed Wall

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Keywords

Excavation,
Numerical modeling,
Nailing,
Building.

Abstract

Today, the demand for underground spaces rises due to the vertical growth of cities. Excavation operations for constructing car parking in residential and commercial buildings are an example of creating such spaces. The assurance of excavation stability by the aid of different systems is of high importance in temporary excavation operations in urban areas. Nailing stabilization, used to stabilize excavations, is the area of focus nowadays. Conventionally, soil nailing and the analysis of excavation performance are executed as overload analysis where the direct effect of buildings adjacent to the excavation is not taken into account. Therefore, this study aimed to evaluate the mutual effect of excavations and buildings using ABAQUS. This study used three different buildings with different foundations: a 2-story building, a 5-story building and an 8-story building. The results indicated that as the number of stories increases, the lateral displacement of excavation and the subsidence of adjacent earth increase. Moreover, it was concluded that piles decrease the lateral displacement of excavation wall and subsidence so that in the presence of disconnected and connected piles, lateral displacement decreased by 45% and 50%, respectively and subsidence decreased by 38%.

1. Introduction

Today, the accelerated movement of the world along with the increased demand for urbanization has highlighted the problem of low urban spaces. Constructing various engineering structures such as buildings, underground intersections and subways, increases the demand for excavation operations in cities. In many areas, the small size of lands and the negligible distance between buildings has converted excavation operations to a worrying and horrific event. Excavations cause deformations to soil mass and adjacent buildings as they make serious changes to the distribution of stress. In excavation operations in urban areas, controlling the deformation of soil and adjacent buildings has been always of high importance as they may cause damages to buildings.

Metallic reinforcements, such as nails and anchors, are widely used to reinforce walls in road-construction and excavation projects [1]. Different parameters including soil type, soil layers, bedrock type, ground water level, climate and geographical conditions such as precipitation, seismic status of site, excavation depth, existence/no-existence, and the quality, of adjacent structural loads affecting retaining structure, financial limitations and engineering judgments are important subjects to be discussed in determining the type of excavation stabilization. Nailing is a typical technique used to stabilize excavations. It has received great attention due to high execution speed.

Numerical techniques are widely used in wall and soil slope stabilization problems [1]. In addition, different case studies and numerical analyses are used to evaluate excavation performance [2-4]. Singh and Babu evaluated the effect of different soil behavior models on excavation performance using finite element. Their results indicated that more advanced models offer more realistic results [5]. Jiang et al evaluated nailing-reinforced excavations using Flac finite difference software. Their results showed that as excavation depth increases, the deformation of excavation wall and the subsidence of adjacent earth increase [6]. Qi and Jiang studied the effect of nail-reinforced excavation using 3D analyses. Their results showed that nailing system remarkably decreases the deformation of excavation wall [7]. Ghareh evaluated excavation performance in cohesive/non-cohesive lands using numerical analyses. Their results showed the direct effect of soil properties on excavation wall [8].

Relying on case studies and numerical and probability analyses, Naeimifar et al studied the effect of nailing system on stabilizing deep excavations and presented the damage level of adjacent structures using damage potential function [9]. Zolghadr et al. evaluated nailed-wall performance using the survey results of a case study conducted on a project in

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Tehran. Their results showed that the magnitude of modeled horizontal displacement is greater than that of the measured one [4].

In a research, the effect of movement due to excavation, on the adjacent buildings after installation of inclined struts was investigated. To this end, a series of 2D finite element numerical simulations were performed. In these simulations, excavation has modeled considering the parameters of the adjacent building and the inclined struts. In order to examine the results of numerical analysis, adjacent building performance criteria were used. 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 [10]. In another research concerns the performance of excavation walls supported by rock nails in rock masses having joints and damage levels of a structure adjacent to excavation area, using the results of numerical investigation. For this purpose, parameters such as wall deflections included cantilever and bulging displacements, settlement under structure and settlement ratio were investigated. In this regard, joints inclination and joints spacing effects were evaluated for this point. To evaluate the effects of mentioned parameters on the performance of excavation wall and building damage caused by wall deflections, a set of calibrated 2D finite element models were developed by considering all interactions between nail-rock-structure, anisotropic properties of jointed rock medium and staged construction process. The results of investigation indicated that different parameters such as anisotropy of rocks, joints inclination have significant effects on performance of excavation walls supported by rock nails, and damage levels of structures adjacent to the excavation area [11].

Maio et al., modeled piles adjacent to excavation using 3D finite element. They discovered that the response of a single pile depends on pile stiffness factor, soil mass displacement, pile cap specifications, soil displacement form and the thickness of moving soil layer. The harder is the pile and the more uniform is the soil displacement, the higher is the moment applied to the pile [12].

Taking a look at previous studies reveals that many of them have evaluated the effect of adjacent buildings in the form of overload analyses and have not considered the direct effect of excavation on the studied buildings. The same trend is observed in excavation design booklets. Therefore, this study models buildings adjacent to excavation in order to evaluate the effect of excavation on buildings performance. This study first visited different buildings adjacent to excavation in different projects and considered three building types. Then, it designed the buildings in ETABS and SAFE and extracted dimensional specifications. Next, it conducted stability and stress-strain analyses using SLOPE/W and ABAQUS.

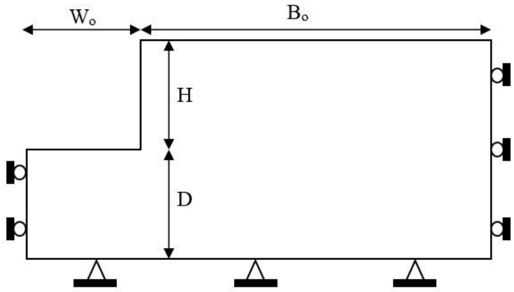

Figure 1. Dimensions and boundary conditions of model

2. Modeling

2.1. Building Design

Figure 1 shows the dimensions and boundary conditions used to model excavation geometry. Standard conditions were defined for boundary conditions where the bottom of model is fastened in both vertical and horizontal directions and lateral boundaries are fastened only in horizontal direction with allowable vertical displacement which is proportional to the type of problem. Assuming that the bedrock is located at depth=21m, we have H=14m, W_0=0.5m, B_0=3(D+H) and D=0.5H [13, 14]. The studied building was designed in SAP2000 as a two dimensional steel frame and in accordance with Iranian typical codes where three spans with a width of 4 m are considered and the height of stories is considered to be 3m. The buildings were modeled with dead and live loads of 500 kg/m^2 and 200 kg/m^2, respectively and with a 4m load bearing span for each beam. Tables 1 and 2 show the specifications of the cross sections of the designed buildings frame and the foundation dimension of each building, respectively. Figures 2 and 3 show the schematic view of the designed 2-story and 5-story buildings, respectively.

2.2. Excavation Design and Analysis Parameters

To determine the number and layout of nails in walls, stability analysis was conducted using Slope/w and in accordance with FHWA nailing code [15]. Safety factor was considered to be 1.35 according to this code. Figure 4 shows a sample analysis. Table 3 shows the number and layout of nails considering adjacent building. The cross section of excavation wall in lateral direction was considered to be as Figure 5 where S_H, S_V, S_{V0} and S_{VN} are horizontal distance of nails, vertical distance of nails, distance of the first nail from ground level and distance of the last nail from the bottom of excavation, respectively.

Table 1. The typical sections of 2, 5 and 8 story building (units in mm)

No. of stories	Beam srctions	Column sections
2	IPE 240	Box 140×10
5	IPE 240 & 270	Box 160×10 & 200×20
8	IPE 270 & 300	Box 160×10 & 180×10 & 200×20

Table 2. Foundation dimension (units in m)

No. of stories	Type of foundation	dimension
2	single	2×0.7
5	spread	14×1
8	spread	14×1.2

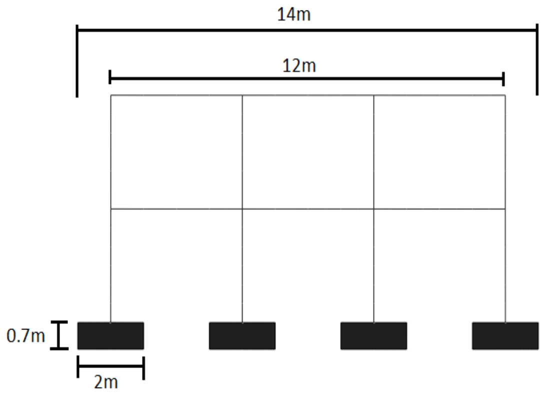

Figure 2. Schematic view of 2-story

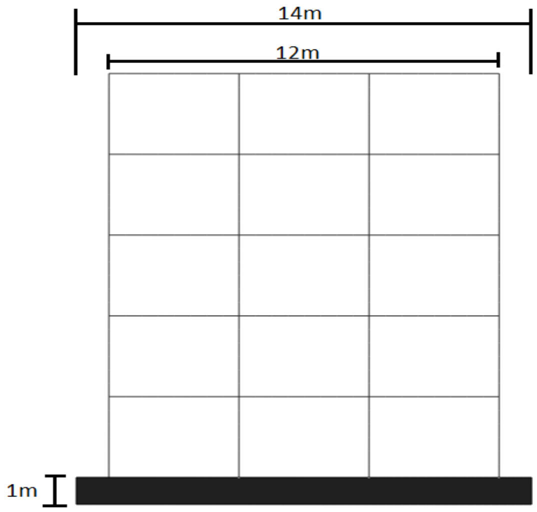

Figure 3. Schematic view of 5-story

Nailing-supported excavation was modeled using ABAQUS and soil behavior was modeled using Mohr-Coulomb's behavioral model. This study uses the elasto-plastic model with Mohr-Coulomb's (MC) disruption criterion as the behavioral model. Therefore, the bottom of excavation will experience a large uplift which is an unrealistic condition. The reason may be traced in the fact that Mohr-Coulomb's model considers the same modulus of elasticity for soil in both loading and unloading conditions. To solve the problem, the unloading area was determined considering soil type and, then, its modulus of elasticity was considered to be 3 times higher than that of loading area [16]. Table 4 shows soil parameters [14]. To model nailing area, the modulus of elasticity was selected from relation (1) where E_{eq} is the equivalent modulus of elasticity of excavation (combination of bar and grout), E_n and E_g are the modulus of elasticity of steel and grout, respectively, A_n and A_g are the cross sections of steel and grout, respectively and A is the cross section of whole excavation.

$$E_{eq} = E_n\left(\frac{A_n}{A}\right) + E_g\left(\frac{A_g}{A}\right) \quad (1)$$

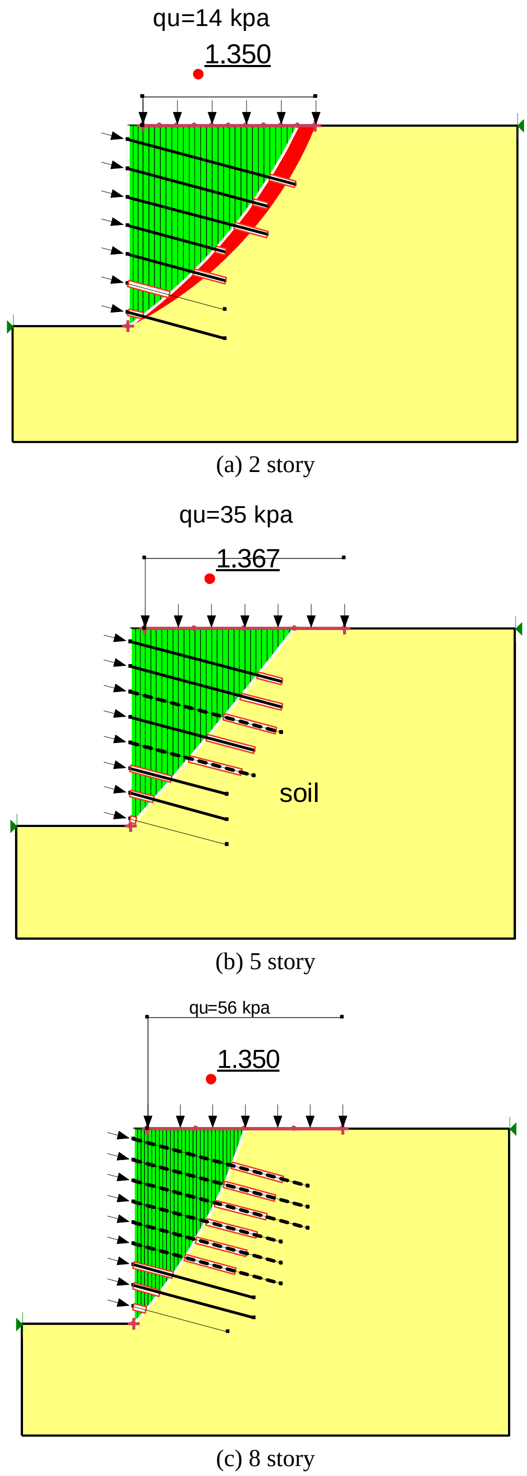

Figure 4. Global factor safety in SLOPE/W

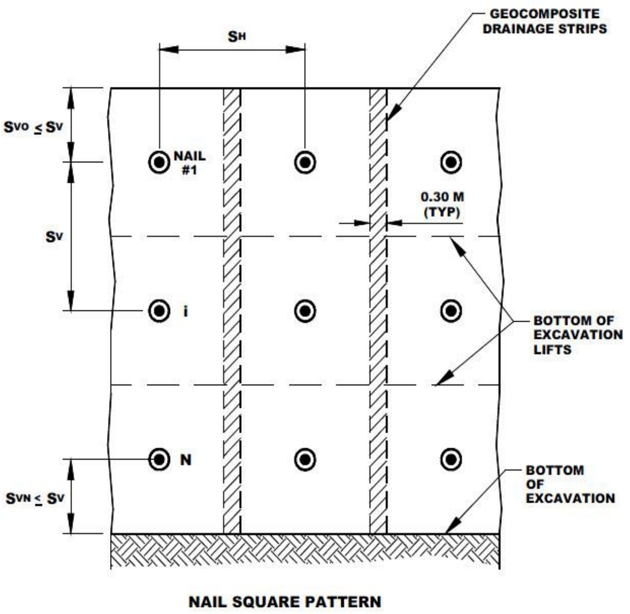

Figure 5. Soil nail patterns on wall face

Table 3. Layout of soil nail wall

No. of stories	Length of nail	S_H	S_V	S_{VO}	S_{VN}
2	7, 10 and 12	2	2	1	1
5	7, 9 and 11	1.9	1.8	0.9	0.5
8	9, 11 and 13	1.8	1.5	0.75	1.25

Table 4. Soil parameters

γ (kN/m³)	C (kPa)	φ (deg)	ψ (deg)	υ	E (MPa)
20	30	36	6	0.3	80

Table 5. Specifications of concrete

γ (kN/m³)	υ	E (GPa)
25	0.2	25

Cap connected/disconnected piles were used to design the studied 8-story building. The dimensions of piles were considered to be constant, pile diameter was considered to be 1 m and a 10 m pile was used beneath each column. Foundation and piles were modeled as elastic modeling. Table 5 shows the specifications of foundation concrete and piles. According to the Iranian codes, it is not necessary to consider earthquake load in temporary conditions of excavation analysis. In addition, the dead load of the building as well as adjacent buildings to the studied area should be completely taken into account in the process of excavation stability analysis. In order to apply the weight of adjacent structure to each story, the total sum of deal and live loads set in building design in SAP2000 was considered.

Joint surface element was used to make connection between structural and soil elements. To this end, the reduction factor (R_{inter}) of soil foundation and pile wall interface was derived from Eqs. (2) and (3) and it was considered to be 0.75 based on previous studies [17, 18].

$$C_{inter} = R_{inter} \times C_{soil} \quad (2)$$

$$tan(\varphi)_{inter} = R_{inter} \times tan(\varphi)_{soil} \quad (3)$$

where C_{inter}, C_{soil}, φ_{inter} and φ_{soil} are interface coherence, soil coherence, interface friction angle and soil friction angle, respectively. In all analyses, the distance of adjacent building was considered to be 1 m. Figure 6 shows a sample meshing of the simulated model. The Six-node elements of CPE6M were used for soil and foundation meshing. In addition, B21, B22 and T2D2 were used for structural elements (building and shotcrete) and nails meshing, respectively. Fine meshes were used in the areas in the vicinity of excavation due to the sensitivity and accuracy required for the results of these areas.

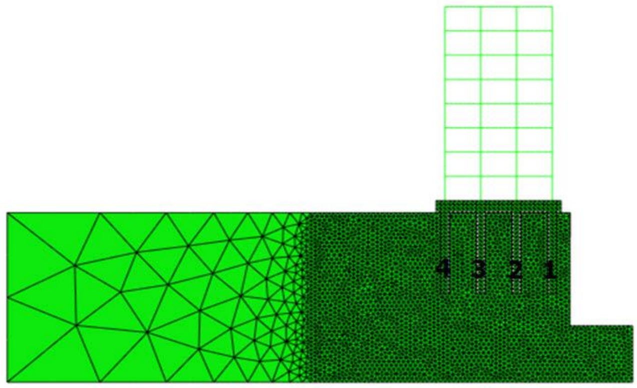

Figure 6. Simulated model

3. Validation

In order to investigate the validity of the results, the excavation with the height of 10 meters which has been stabilized by nailing system in the study by Singh and Babu was reinvestigated [9]. In that study the length of the nails was 7 meters, located at 1 meter vertical and horizontal distances. The angles of the nails were considered with a 15-meter horizon. 5 excavation phases have been performed in this study; in each phase 2 meters soil was excavated and 2 rows of nails along with a shotcrete of soil nail wall with 20-centimeter thickness were executed. MC soil model was used to model the soil behavior. The results of this investigation are shown in Figures 7 and 8. As it is clear, the results of this study are consistent with the findings by Singh and Babu.

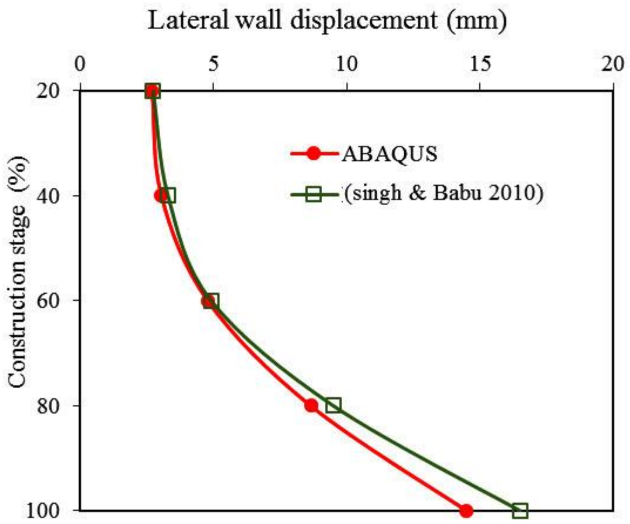

Figure 7. Predicted lateral displacement of wall facing

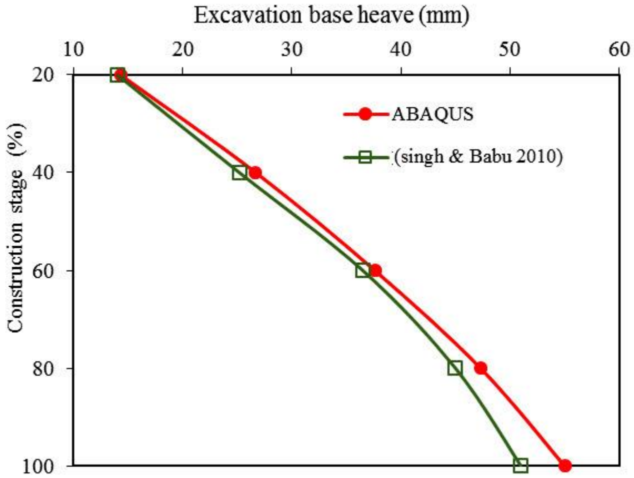

Figure 8. Predicted excavation base have

4. Results and Discussions

Taking lateral deformation of excavation wall and building as well as the subsidence of earth into consideration is of high importance in excavation design. The numerical analyses of buildings adjacent to the studied excavations are discussed in the following.

Figure 9 shows the effect of excavation on the maximum horizontal displacement of wall at the end of excavation operation. According to this figure, as the number of stories increases, the deformation of excavation wall increases. This deformation is in the form of bulging with the maximum value of 7 to 9 m at the middle of excavation depth. In addition, piles decrease horizontal displacement of excavation wall so that for an 8-story building the maximum horizontal displacement of excavation in the presence of connected/not-connected piles decreases by 17.65 compared to excavations with no pile. Considering the allowable horizontal displacement, which equals to 0.002 of excavation height, the maximum horizontal displacement lies inside permissible range in all models [15].

Figure 10 shows the subsidence of adjacent earth at the end of excavation of the 2-story, 5-story and 8-story buildings. According to the figure, earth subsidence follows a non-uniform trend and the maximum subsidence is observed in the 2-story building at 6 m from wall edge while for other buildings, it varies from the vicinity of excavation to 15m from excavation edge. This means that its variation range equals to the width of foundation and by the increase of distance from foundation edge, earth subsidence decreases gradually. Moreover, piles remarkably decrease the subsidence of earth beneath foundation. No significant difference is observed in subsidence reduction between connected and non-connected piles and both have the same effect on subsidence. The maximum subsidence of pile-supported foundations decreases by 38% in the 8-story building compared to the case where no pile is used. The comparison of subsidence values derived from numerical models and the permissible subsidence values, in accordance with relevant codes, shows that the maximum subsidence lies inside permissible range in all buildings.

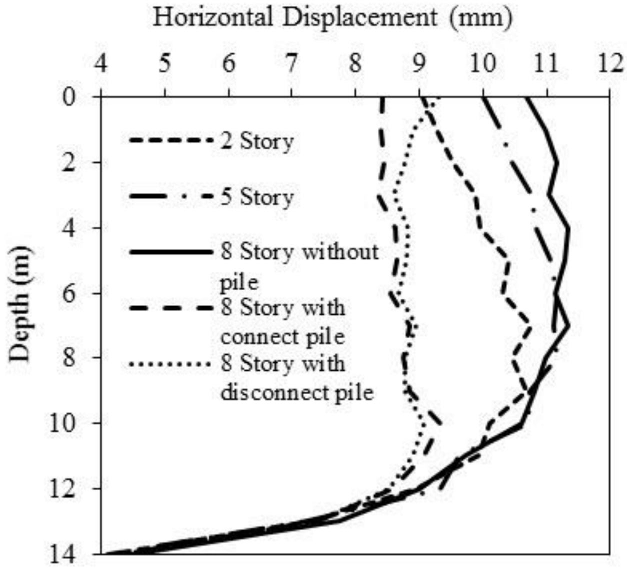

Figure 9. Maximum horizontal displacement of wall facing

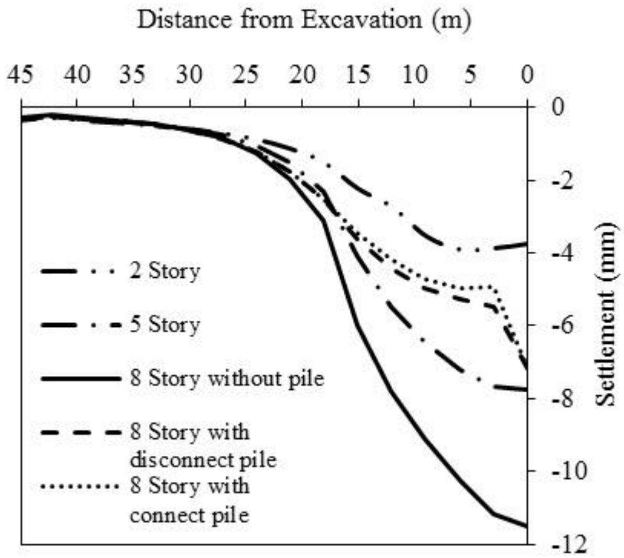

Figure 10. Settlement of ground surface

Figures 11 and 12 show the maximum lateral displacement of buildings under excavation effect and Figure 13 shows the maximum lateral displacement of buildings adjacent to the excavation at the end of excavation operation. According to the figures, the maximum lateral displacement of the 2-story building occurs at the column base while in the 5-story and 8-story buildings, it occurs at the highest story. The difference in the location of the maximum lateral displacement between the 2-story building and other buildings is rooted in foundation type because the 2-story building has isolated foundation. According to Figure 13, for the 8-story building, the maximum lateral displacement occurs in the absence of pile while the existence of pile in other buildings decreases lateral displacement. Connected and non-connected piles decrease subsidence by 45% and 50%, respectively.

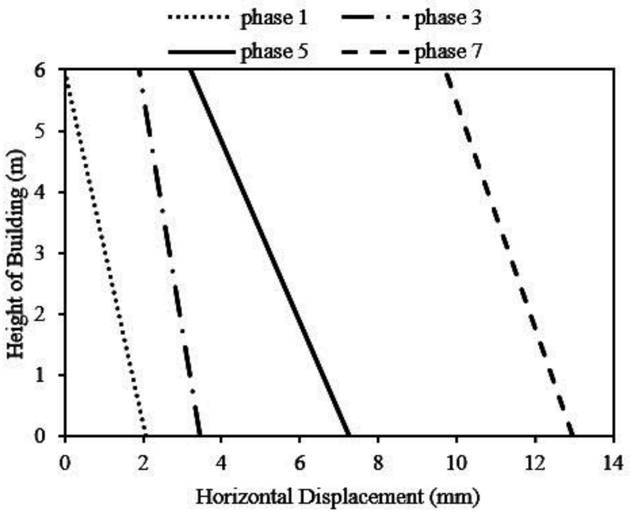

Figure 11. Maximum horizontal displacement for 2-story

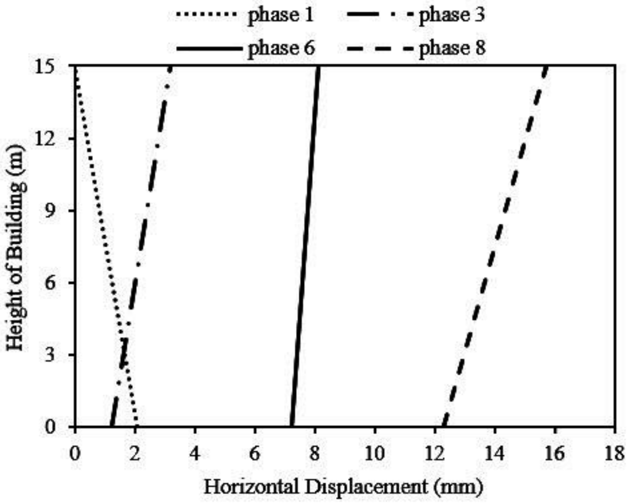

Figure 12. Maximum horizontal displacement for 5-story

Figure 6 shows pile numbering method used to present results. Figures 14 and 15 show the distribution of bending moment in connected and non-connected piles as the deep foundations of the 8-story building. According to Figure 14, the distribution of bending moment in piles that are closer to the excavation wall differs from that of farther piles so that the maximum bending moment in former group (pile number 3 and 4) occurs in the vicinity of the point that the pile is connected to the cap while in later group it occurs at depths 6m to 8m. In connected piles, the magnitude of internal force of pile increases due to the use of structural capacity so that the pile that is closer to the excavation wall experience higher displacements associated with higher forces originated from the closeness to the excavation wall.

Figure 15 shows the distribution of bending moment in disconnected piles. According to this figure, the distribution of bending moment differs from supported piles. In this case, the maximum bending moment of lateral piles (number 1 and 4) is higher than that of middle piles (number 2 and 3). The reason is that disconnected piles fail to use structural capacity and move freely. In this case, the farthest pile experience higher moments due to larger rotation range. In addition, the maximum bending moment in excavation-adjacent piles is generated at the end of pile while for farther piles it is generated at depth 7m to 8m.

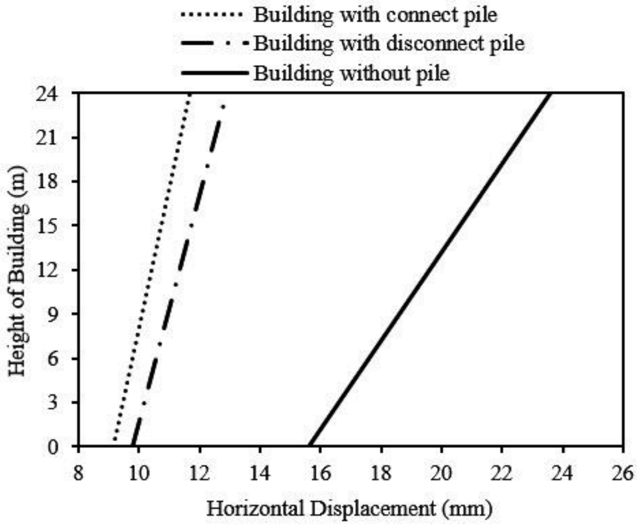

Figure 13. Maximum horizontal displacement for 8-story at the end of excavation

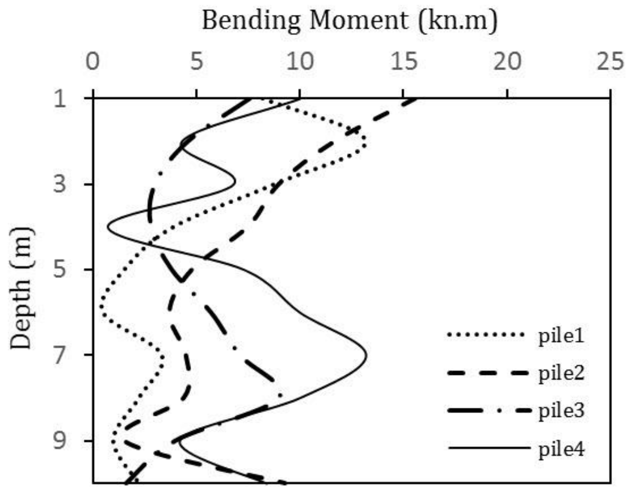

Figure 14. Bending moment of connected piles

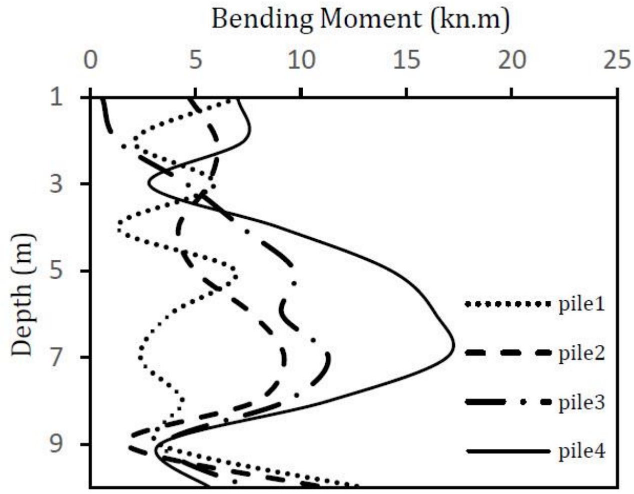

Figure 15. Bending moment of disconnected piles

5. Conclusions

This study aimed to evaluate the performance of buildings adjacent to nailing-stabilized excavations. Therefore, it used ABAQUS for this purpose. The important results are as follows:

1) The number of stories of excavation-adjacent buildings has a direct effect on the lateral displacement of the buildings so that as the number of stories increases, lateral displacement increases.

2) Piles significantly decrease the lateral displacement of buildings so that for an 8-story building, lateral drift decreased by 45% and 50% for connected and disconnected piles, respectively compared to no pile case.

3) Connected piles show better performance in reducing lateral displacement compared to disconnected piles so that they reduce lateral displacement by 10% compared to disconnected piles.

4) Excavation-induced subsidence is not uniform and the maximum subsidence varies with foundation type so that for an isolated foundation, the maximum subsidence occurs at 6m from wall edge while for a mat foundation it occurs in the vicinity of excavation wall.

5) Piles considerably reduce the subsidence of earth beneath the foundation. The performance of connected and disconnected piles in reducing subsidence is not significant and both types have the same effect on earth subsidence. The maximum subsidence of pile-supported foundations in the 8-story building reduced by 38% compared to non-pile-supported buildings.

6) As the number of stories increase, the deformation of excavation wall increases. In addition, piles reduce the horizontal displacement of excavation wall so that in the 8-story building, the maximum horizontal displacement reduced by 17.6% in the presence of pile (connected and disconnected) compared to no pile case.

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