

# STUDY OF CONVEX CORNERS' EFFECT ON THE DISPLACEMENTS INDUCED BY SOIL-NAILED EXCAVATIONS

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**Abstract.** In deep excavations, because of time, budget, and computational tools limitation, two-dimensional analyses (plane strain analyses) rather than three-dimensional ones are often used for controlling factors of safety and displacements. In most excavation projects, the excavation plan includes convex and concave corners. Unlike concave corners, the use of two-dimensional analysis for convex corners is non-conservative. In the present study, by using three-dimensional numerical modellings and comparing 3D and 2D results, the effects of convex corners on the displacements induced by soil-nailed excavations are studied for two types of soil: sand (granular soil) and clay (cohesive soil). The results of the study indicate that the length of the zone affected by the convex corner (the zone along the wall and around the convex corner where the values of the displacements are greater than the corresponding two-dimensional values) is about 0.75 to 1 times the excavation's depth. The results also show that although the horizontal soil nails are executed easier and prevent interference of nails which cross, but applying an appropriate angle over the horizon (about 10 degrees) to the soil nails can reduce the wall displacements. Furthermore, it was found that applying azimuth to the soil nails in the area affected by the convex corner, significantly increased the displacements of this area. Lastly, it has been suggested that to reduce

the displacements in the zone affected by the convex corner, increasing the length of the soil nails is more effective than decreasing their horizontal spacing.

## Keywords

Soil-nailed walls, convex corner, deep excavation, FEM, three-dimensional analysis, plane strain ratio.

## 1. Introduction

In most excavation projects, there are several corners (concave or convex) in the excavation plan. Although excavation-induced displacements and behavior result in three-dimensional deformations, the two-dimensional plane strain analyses are generally conducted in engineering practice. Unlike concave corners, in which the use of two-dimensional analysis is conservative, for convex corners it is non-conservative and executing the project, based on two-dimensional designs, can lead to disaster. Hence, many studies have been done on the effects of corners' geometry on excavation's stability and its displacements.

Ou et al. (1996) [1] studied the effect of the corner existence on the displacements of an excavation with soft to medium clayey subsoil stratum, by using a nonlinear, three-dimensional finite element method. By doing a series of parametric studies, a relationship is developed to estimate three-dimensional maximum wall displacement of an excavation based on two-dimensional results. Lee et al. (1998) [2] discussed the effects of corners on the wall deflection and ground movement around multi-strutted deep excavations. They showed that where corner effects are significant, three-dimensional analysis may be able to offer significantly better predictions of movement than two-dimensional analysis. By comparing several excavation projects where corner effects were considered or observed, they concluded that the effects of corners depend on three factors: the length-to-depth ratio of the excavation, the depth to a relatively stiff stratum, and the stiffness of the strutting system.

Finno et al. (2007) [3] conducted 150 finite-element simulations to study the effects of excavation geometry (length, width, and depth of excavation) and wall system stiffness in clays. They showed when the excavated length normalized by the excavated depth of an excavation wall is greater than 6, results of plane strain simulations yield the same displacements in the center of that wall as those computed by a three-dimensional simulation. Zhao et al. (2014) [4] found that for an irregular shaped excavation, the settlement pattern of soil layers and structures was greatly affected by the concave and convex location. They showed that the affected areas of soil settlement near the concave and convex location were much different from the middle of the excavation and due to the corner effect, the adjacent building was not only suffered from settlement but also torsional deformation.

Szepeshazi et al. (2016) [5], by performing a set of three-dimensional finite element analyses, showed that the bending moments of diaphragm walls increased significantly in the vicinity of the corners. Moradi et al. (2020) [6] conducted four centrifuge model tests to investigate the effect of convex corners on the deformation of soil-nailed walls and evaluate the influence of the soil-nail

layout on wall behavior. Their results indicated that the deflection pattern of the convex corners was affected by the soil nails inclination angle over the horizon and that the wall facing played a major role in controlling wall deformation in models with a three-dimensional geometry. Hsiung et al. (2020) [7] concluded that excavation geometry, distance from the corner, the ratio of the wall embedded depth to the excavation depth, and the wall thickness have significant influences on the displacements of corners.

Moreover, several other researches have been conducted on the effects of three-dimensional analyses of excavations [8]-[12]. In most previous studies, the retaining structures for stabilizing the excavations have been diaphragm walls or braced systems and fewer studies have covered soil nail walls. Furthermore, it is thought that investigating approaches to decrease the displacements of affected area by convex corners, deserves to be further explored.

This study aims to assess the effect of convex corners on the deflections induced by soil-nailed excavations. For this purpose, after verifying the employed FEM software by measured results of one soil-nailed excavation, many three-dimensionally analyses have been conducted for studying the aforementioned effect. The horizontal displacements of the convex corner and settlements of the ground surface in 3D analyses have been compared to the corresponding amounts in plane strain analyses, for two types of soil (granular and cohesive soils). Furthermore, the effects of applying inclination and azimuth to the soil nails on the induced displacements have been investigated. Moreover, two approaches (increasing the nails length and decreasing their horizontal spacing) have been studied to examine their ability to decrease the deflections of convex corner. Findings of this study can be helpful to reduce the convex corner's displacements and design soil-nailed excavations with convex corners more effectively.

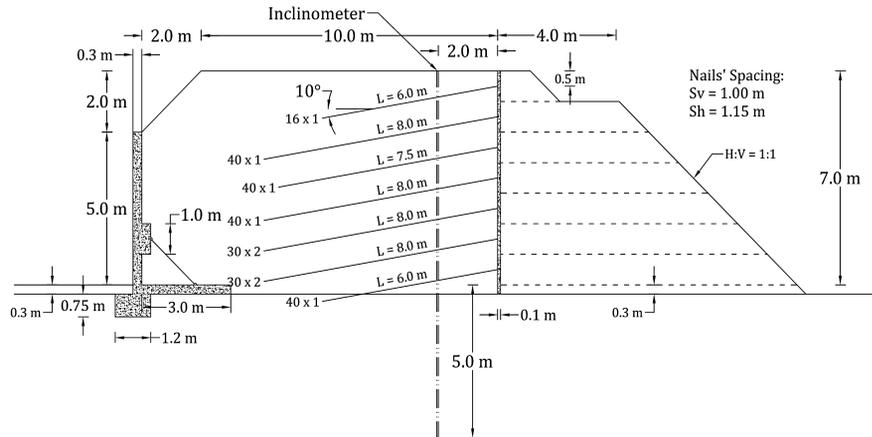


Fig. 1: Properties of soils used in the FE analyses for the soil-nailed wall in the CLOUTERRE project [13, 14].

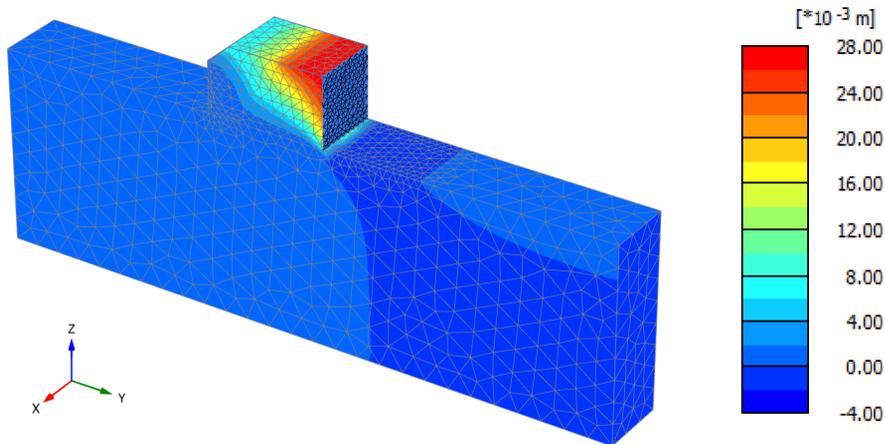


Fig. 2: Horizontal displacements of the soil-nailed wall for the CLOUTERRE project (for case 1).

## 2. Methodology

### 2.1. Verification

In order to verify the FEM software and soil behavior model which have been used in this study, the results of one of the walls which has been published by Fan & Luo (2008) [13], have been used. The soil-nailed wall was a full-scale test conducted in 1986 for the French national research project CLOUTERRE, which was constructed in an experimental backfill, built near Paris on a dense sand formation [14].

The soil-nailed wall was 7.0 m high, 7.5 m wide, and constrained between two lateral walls

covered with a double layer of polyethylene sheet greased in between to ensure plane strain conditions. The wall was built by alternating 1.00 m high excavations with the placing of nails at a horizontal spacing of 1.15 m. The nails were inclined 10 degrees with respect to the horizon and their lengths ranged from 6 to 8 m (grouted diameter = 63 mm). The nails were made of hollow aluminum pipes. A reinforced concrete retaining wall was constructed behind the backfill prior to placing the nails. A facing, made of a mesh-reinforced shotcrete, was installed after placing the nails (Fig. 1) [13, 14].

The Hardening Soil Model (HS Model) has been employed for defining the behavior of verification models' soils. Tab. 1 shows the val-

ues of soil properties used in the FE analyses. It should be mentioned that seven different models with different values for  $E_{\text{od}}^{\text{ref}}$  (tangent oedometer stiffness),  $E_{\text{ur}}^{\text{ref}}$  (unloading/reloading stiffness), and  $m$  (power for stress-level dependency of stiffness) have been studied. Tab. 2 shows the values of the aforementioned parameters for the cases studied.

**Tab. 1:** Properties of soils used in the FE analyses for the soil-nailed wall in the CLOUTERRE project [13, 14].

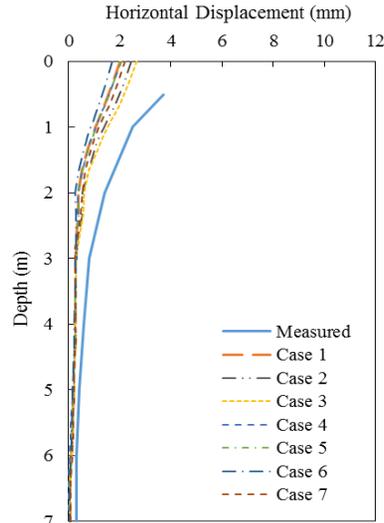
		Backfill	Foundation Soil	
Unit weight	$[\gamma]$	kN/m <sup>3</sup>	16.6	17.0
Cohesion	$[c']$	kN/m <sup>2</sup>	3	0
Friction angle	$[\varphi']$	Deg.	38	36
Dilatancy angle	$[\psi]$	Deg.	25	20
Secant stiffness	$[E_{50}^{\text{ref}}]$	kN/m <sup>2</sup>	15500	42000

**Tab. 2:** Stiffness properties of soils used in the FE analyses for the verification models

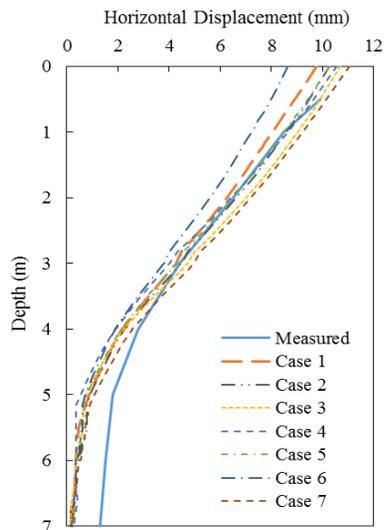
Case No.	$E_{\text{od}}^{\text{ref}}/E_{50}^{\text{ref}}$	$E_{\text{ur}}^{\text{ref}}/E_{50}^{\text{ref}}$	$m$
1	1	3	0.5
2	1	4	0.5
3	1	5	0.5
4	0.50	3	0.5
5	0.75	3	0.5
6	1	3	0.4
7	1	3	0.6

The geometry of CLOUTERRE project was modelled in PLAXIS 3D V.2017, which is a FEM software, and the computed results were compared to the measured ones. In Fig. 2, the computed horizontal displacements of the soil-nailed wall (for case 1) is shown.

Comparison of the measured and computed horizontal displacements in the backfill at 2 m behind the wall at the end of phase 3 (after installing the third row nails) and phase 5 (after installing the fifth row nails) are shown in Fig. 3. Moreover, Fig. 4 shows comparison of the measured and computed maximum tensile forces ( $T_{\text{max}}$ ) in nails with depth. Also, in Fig. 5, the measured horizontal and vertical earth pressure



(a)

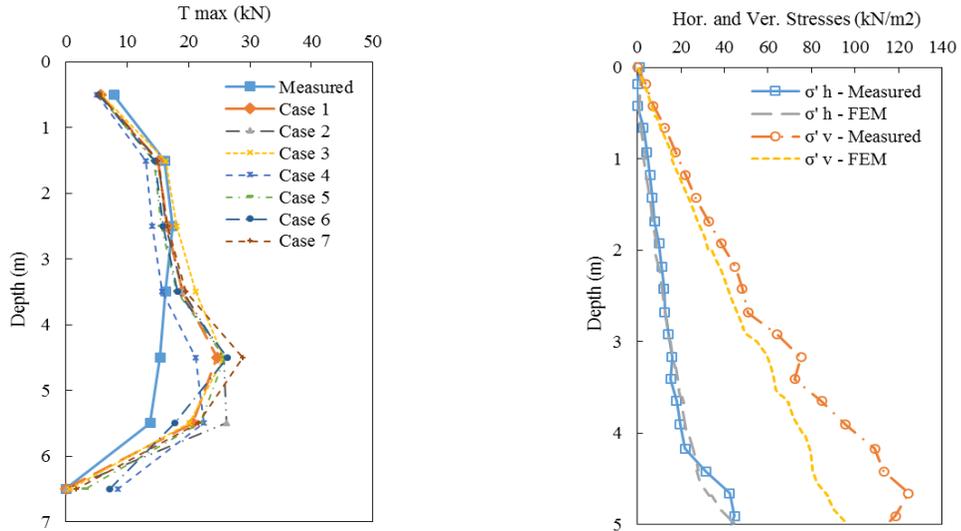


(b)

**Fig. 3:** Comparison of the measured and computed horizontal displacements in the backfill at 2 m behind the wall (a) at the end of phase 3, (b) at the end of phase 5.

distributions in the backfill at 1 m and 3 m behind the wall are compared with the results of FEM modelling (for case 1).

It can be seen that there is a good agreement between the measured values and the obtained

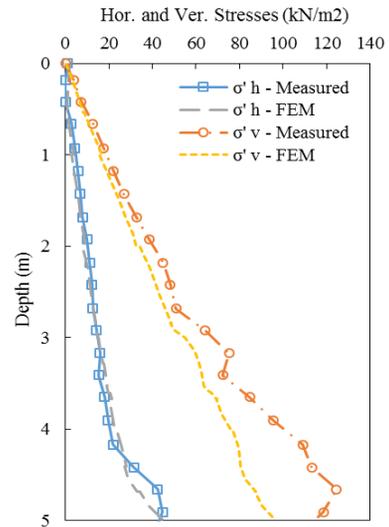


**Fig. 4:** Comparison of the measured and computed maximum tensile forces ( $T_{max}$ ) in nails with depth.

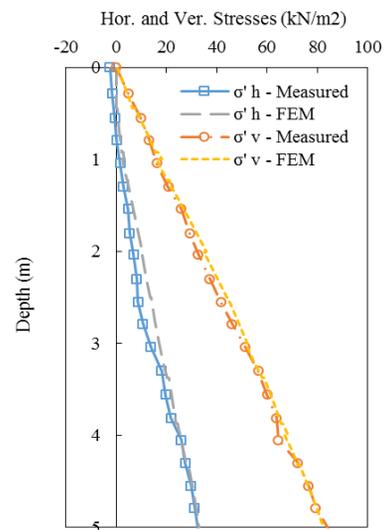
results from FEM modelling. Hence, it can be concluded that the used FEM software is capable of modelling soil-nailed excavations and the Hardening Soil Model (HS model) can be used for evaluating the excavation-induced displacements in this study. The values of parameters mentioned in Tab. 2 for case 1, which are also the software’s default values, have been selected to be used in the following models to study the convex corners’ effect.

## 2.2. Modelling

To study the convex corners’ effect on the displacements induced by soil-nailed excavations, 16-meter excavations have been modelled in this study. As it was mentioned before, the employed FEM software in this study is PLAXIS 3D V.2017. The model’s dimensions were chosen in such a way that the effect of its boundaries on the results was minimized. For this purpose, the length of the soil body behind the wall was considered 3 times the excavation’s depth ( $H$ ) and its length in front of the wall was considered 2 times the excavation’s depth. Also, the ratio of the models’ height to the excavation’s depth is 2.50 ( $H_{soil}/H_{excavation} = 2.50$ ).



(a)



(b)

**Fig. 5:** Comparison of the measured and computed horizontal and vertical earth pressure distributions in the backfill (a) at 1 m from the facing, (b) at 3 m from the facing.

In Fig. 6, a view of the base model and its FE mesh are shown. The level of meshing has been considered to “Fine”. Also, the meshing around the surfaces, lines, and points of the model has been refined for more precise results.

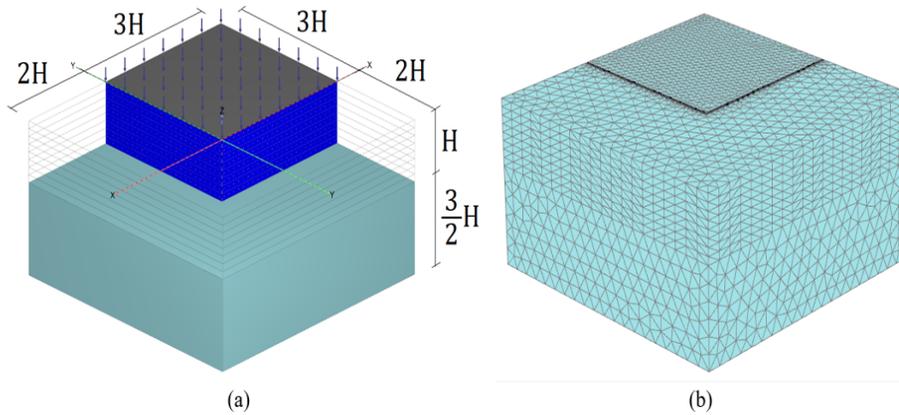


Fig. 6: (a) A view of the base model, (b) FE mesh.

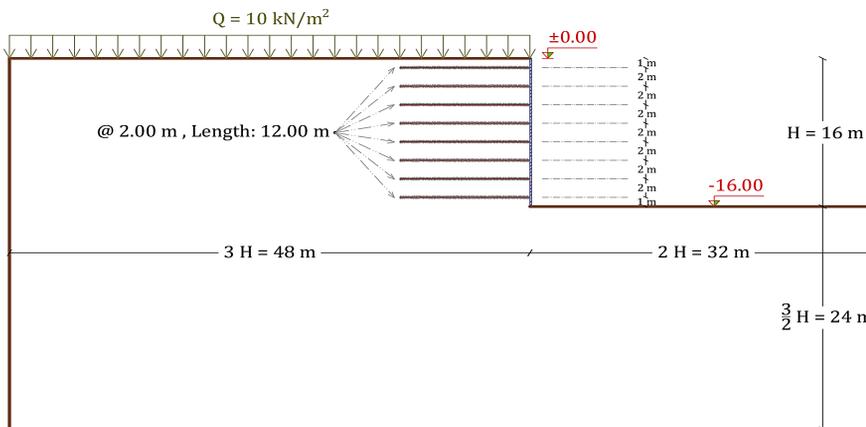


Fig. 7: A schematic cross-section of the model.

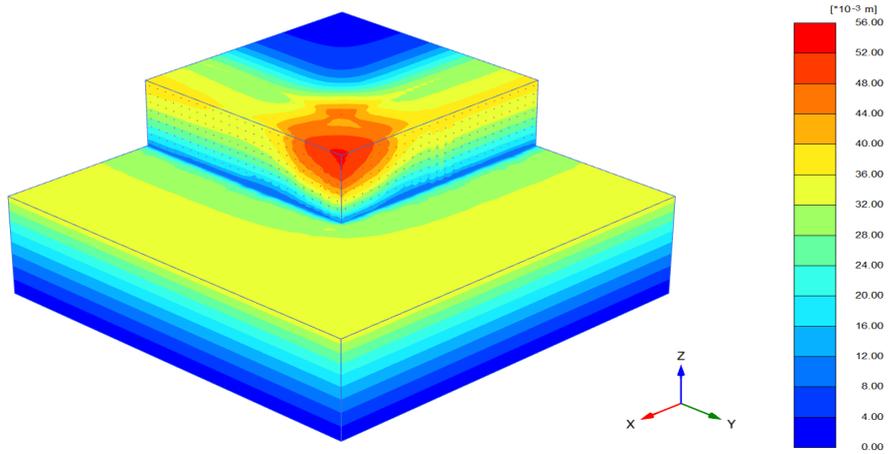
It should be mentioned that the excavation has been done in 2-meter steps and the soil nails' angle has been considered 0 over the horizon. Furthermore, the surcharge applied at the top of excavation is assumed to be  $10\text{ kN/m}^2$  ( $\approx 1\text{ ton/m}^2$ ). In Fig. 7, a schematic cross-section of the model is shown.

In order to investigate the effect of convex corners for both granular and cohesive soils, all studies have been done on two types of soils (sand and clay). In Tab. 3, properties of the soils used in the study are shown. Also, Tabs. 4 and 5 show the properties of shotcrete facing and soil nails, respectively. It should be mentioned that for modelling the shotcrete facing and soil nails, 'plate' and 'embedded beam' elements have been used, respectively.

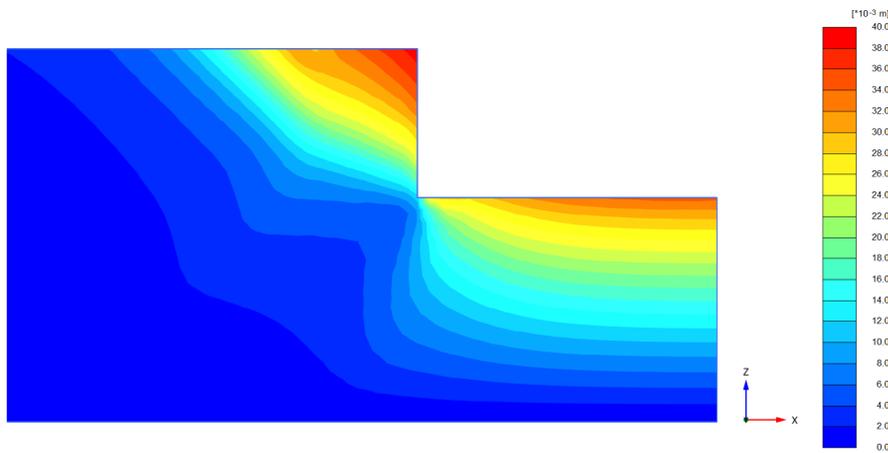
### 3. Results and discussion

After determining properties of soil and used elements and characteristics of the models, three- and two-dimensional analyses were done. Fig. 8 shows the soil's total displacements in 3D and 2D models, for sand. As it can be seen, soil displacements around the convex corner are greater rather than areas which are not affected by it.

In Fig. 9, the horizontal displacement of the corner in 3D analysis was compared to the horizontal displacement of the wall in plane strain analysis, for both types of soil. Also, Fig. 10 shows the comparison of settlements of the ground surface (perpendicular to the wall) in 3D and 2D analyses. As it can be seen, the real induced displacements (in 3D analysis) are consid-



(a)



(b)

**Fig. 8:** Total displacements of soil, for sand (a) 3D model, (b) 2D model.

erably greater than their corresponding values in plane strain analysis. It shows the significance of 3D analysis for excavations with convex corners.

Furthermore, factors of safety (F.S.) of 3D and 2D analyses for both types of soils was obtained. For sand models, 2D and 3D factors of safety are 1.50 and 1.46, respectively. Also, for clay models, 2D and 3D factors of safety are 1.50 and 1.48, respectively. It should be mentioned that the idea of “phi/c reduction” was used for reaching the factors of safety. This idea is that the soil’s strength is gradually reduced and when

failure occurs, the corresponding strength reduction factor can be considered as a factor of safety.

In order to study the effect of corners on the induced displacements, one parameter named the ‘plane strain ratio’ (PSR) has been defined. PSR is equal to the ratio of horizontal displacement of the wall crest at any location along the wall to horizontal displacement of the wall crest in plane strain analysis. Variations of PSR values for both sand and clay are shown in Fig. 11. It can be seen that the length of the zone affected by the convex corner, i.e. the zone along the wall and around the convex corner

**Tab. 3:** Properties of two types of soils used in the study (for Hardening Soil Model).

			Granular Soil (Sand)	Cohesive Soil (Clay)
Material model		-	Hardening Soil	Hardening Soil
Unit weight	$[\gamma]$	$\text{kN/m}^3$	19	17
Cohesion	$[c']$	$\text{kN/m}^2$	5	35
Friction angle	$[\psi']$	Deg.	36	27
Dilatancy angle	$[\psi]$	Deg.	6	0
Power for stress-level dependency of stiffness	$[m]$	-	0.5	0.5
Secant stiffness	$[E_{50}^{\text{ref}}]$	$\text{kN/m}^2$	50000	30000
Tangent oedometer stiffness	$[E_{\text{oad}}^{\text{ref}}]$	$\text{kN/m}^2$	50000	30000
Unloading/reloading stiffness	$[E_{\text{ur}}^{\text{ref}}]$	$\text{kN/m}^2$	150000	90000

**Tab. 4:** Properties of shotcrete facing.

			Shotcrete
Material model		-	Elastic
Thickness	$[t]$	m	0.15
Unit weight	$[\gamma]$	$\text{kN/m}^3$	24
Young's modulus	$[E]$	$\text{kN/m}^2$	$21 \times 10^6$
Poisson's ratio	$[v]$	-	0.20

**Tab. 5:** Properties of soil nails for sand and clay.

			For Sand	For Clay
Material model		-	Elastoplastic	Elastoplastic
Bar diameter	$[d]$	m	0.032	0.032
Borehole diameter	$[d']$	m	0.12	0.12
Bar yield stress	$[\sigma_y]$	$\text{kN/m}^2$	$400 \times 10^3$	$400 \times 10^3$
Bond resistance	$[q_b]$	$\text{kN/m}^2$	180	100
Bar Young's modulus	$[E_s]$	$\text{kN/m}^2$	$200 \times 10^6$	$200 \times 10^6$
Grout Young's modulus	$[E_g]$	$\text{kN/m}^2$	$21 \times 10^6$	$21 \times 10^6$

where the values of the displacements are greater than the corresponding two-dimensional values ( $PSR > 1$ ), is about 0.75 to 1 times the excavation's depth. Also, the length of affected zone in sand is greater than its value in clay. In other words, values greater than 1 for PSR represent the effects of convex corners on the induced displacements.

For models in the next sections, the length of affected area is considered equal to the excavation's depth (Length of affected area = H).

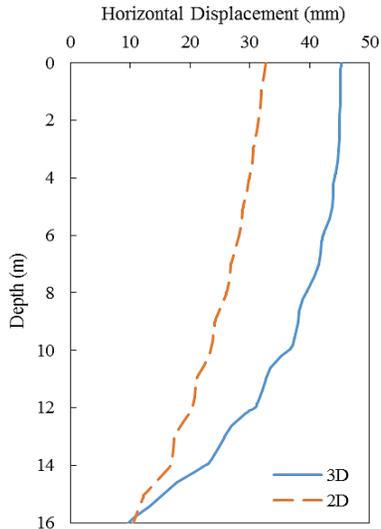
### 3.1. Soil nails inclination

In this section, the effect of applying an angle over the horizon to the soil nails are studied. For this purpose, four angles of 5, 10, 15, and 20 degrees are applied to the nails, for both sand and clay models. In Figs. 12 and 13, the horizontal displacements of the convex corner and the settlements of the ground surface (perpendicular to the wall) for different inclination angles are shown.

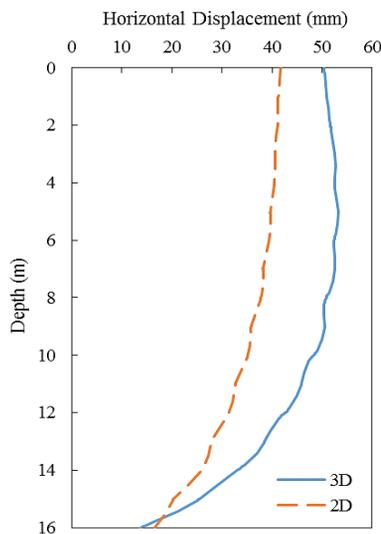
It can be seen that although executing nails horizontally can prevent interference when they cross, but applying an appropriate angle to the horizon to the soil nails can reduce the wall displacements. It is found that an angle of about 10 degrees can be the most efficient, and decreases both lateral and vertical displacements well.

### 3.2. Applying azimuth to the nails

Applying azimuth to the nails which are located within 16 m from the convex corner (in the affected area by convex corner) is another investigation which has been done. In fact, those nails which are located within 16 m from the convex corner were inclined in horizontal plane. In order to study the effect of the soil nails' azimuth on



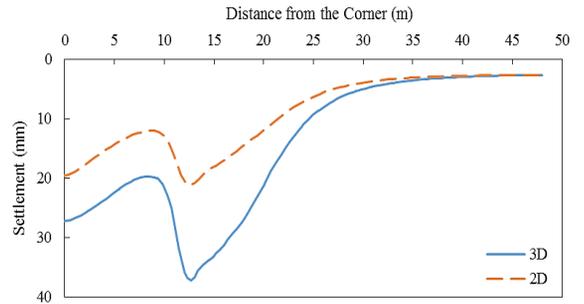
(a)



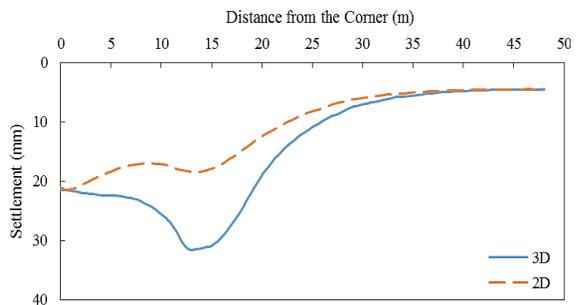
(b)

**Fig. 9:** Comparison of horizontal displacement of the convex corner in 3D analysis and the horizontal displacement of the wall in plane strain (2D) analysis (a) for sand, (b) for clay.

the displacements induced by excavation, three different models were examined for both sand and clay. In the first model, there is no azimuth and in the second one, the azimuth is 45 degrees. The third model's azimuth of nails varies from 0

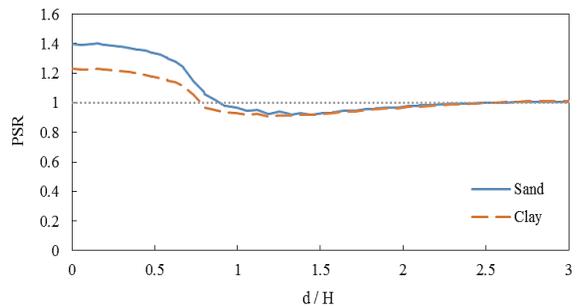


(a)



(b)

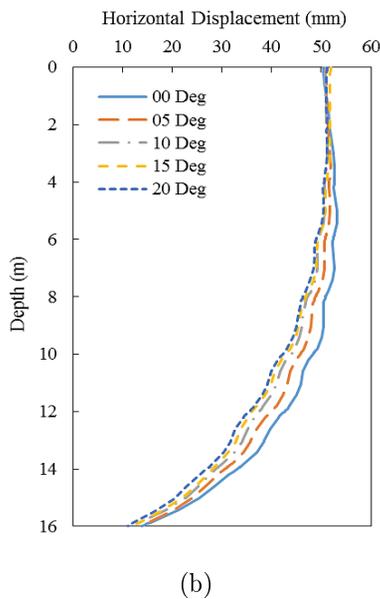
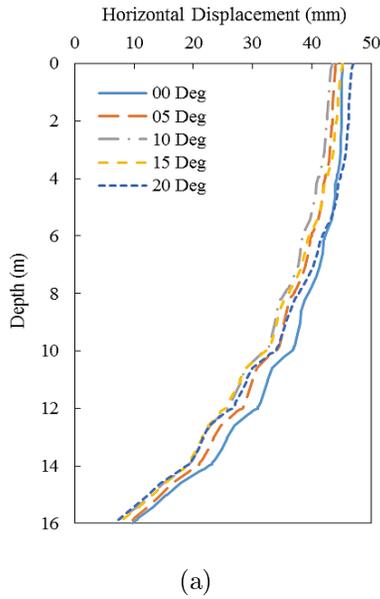
**Fig. 10:** Comparison of settlements of the ground surface (perpendicular to the wall) in 3D and 2D analysis (a) for sand, (b) for clay.



**Fig. 11:** PSR (plane strain ratio) values for horizontal displacements, for sand and clay.

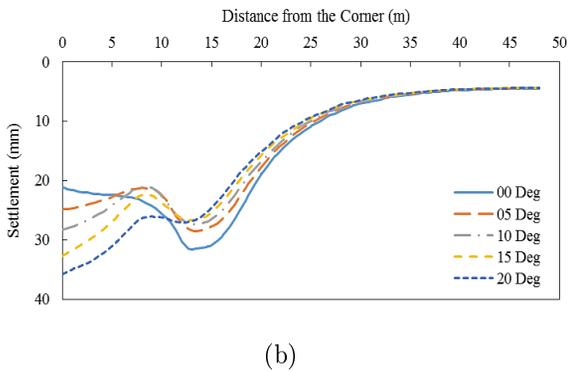
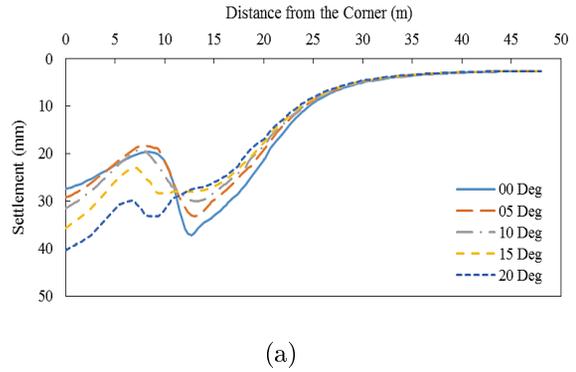
to 45 degrees. Plans of different azimuth models are shown in Fig. 14.

Figures 15 and 16 show the horizontal displacements of the convex corner and the settlements of the ground surface (perpendicular to the wall) for different azimuth conditions, respectively. As it can be seen, applying azimuth to the soil nails in the area affected by the convex



**Fig. 12:** Horizontal displacements of the convex corner for different inclination angles (a) for sand, (b) for clay.

corner, increases the horizontal displacements and settlements.

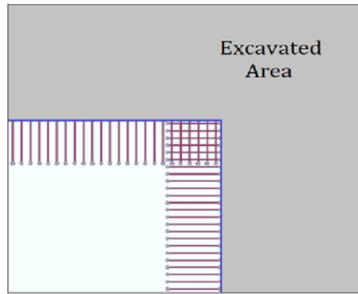


**Fig. 13:** Settlements of the ground surface for different inclination angles (a) for sand, (b) for clay.

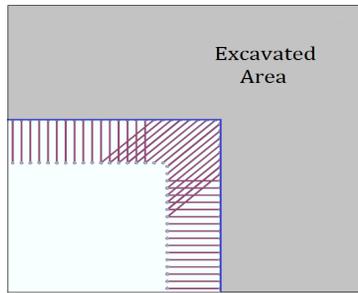
### 3.3. Reinforcing the affected area

To reduce the effect of convex corner on the displacements induced by soil-nailed excavations, two approaches have been examined: increasing the nails length and decreasing their horizontal spacing. In Figs. 17 and 18, the horizontal displacements of the convex corner and the settlements of the ground surface (perpendicular to the wall) for the base model and three reinforced models are shown.

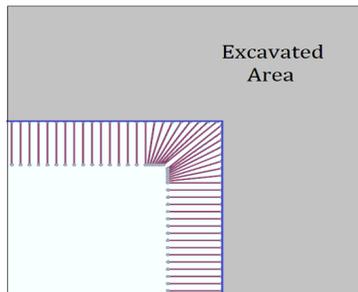
It should be noticed that increasing the nails length or decreasing their horizontal spacing applied only on those nails which were located in the affected area by convex corner. Moreover, the three new models were chosen and modelled in such a way that all of those models increased the total length of the nails equally. It can be seen that increasing the length of the soil nails



(a)



(b)



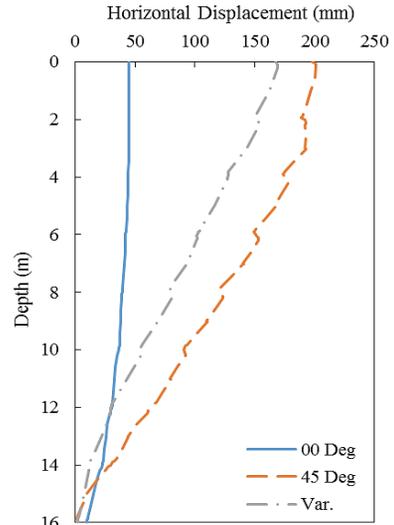
(c)

**Fig. 14:** Plans of different azimuth models (a) no azimuth, (b) azimuth = 45 Deg., (c) variable azimuth.

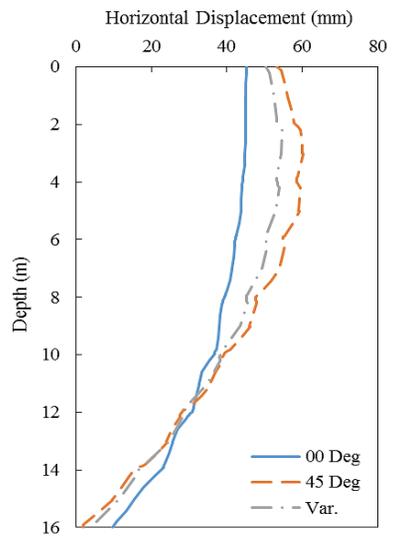
can be a better approach rather than decreasing their horizontal spacing.

#### 4. Conclusion

This study aimed to evaluate the effect of convex corners on the displacements induced by



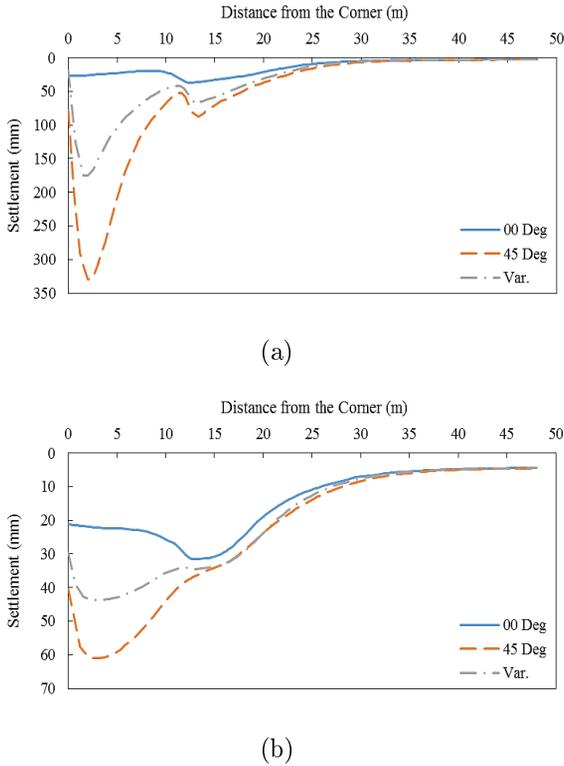
(a)



(b)

**Fig. 15:** Horizontal displacements of the convex corner for different azimuth conditions (a) for sand, (b) for clay.

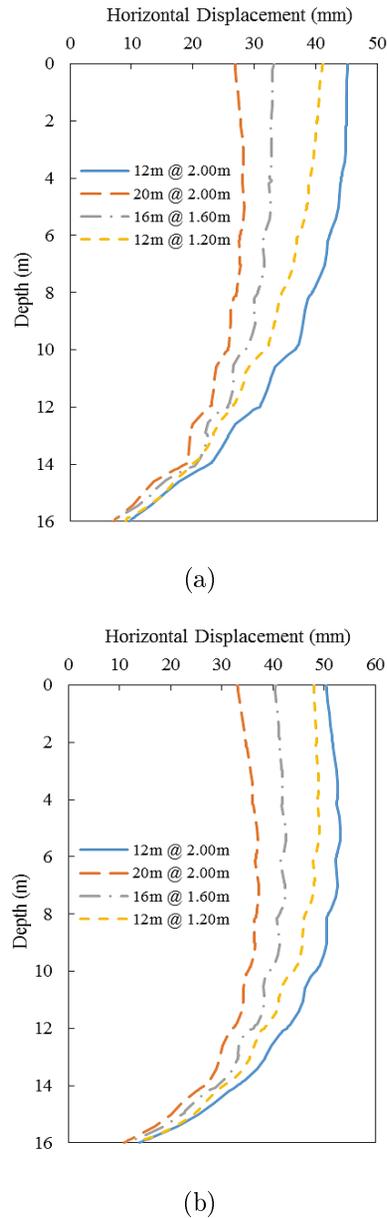
soil-nailed excavations. After reviewing the literature and doing a verification model, it was confirmed that the used FEM software is capable of modelling soil-nailed excavations and the Hardening Soil Model (HS model) can be used for evaluating the excavation-induced displacements in this study. By comparing the results of



**Fig. 16:** Settlements of the ground surface for different azimuth conditions (a) for sand, (b) for clay.

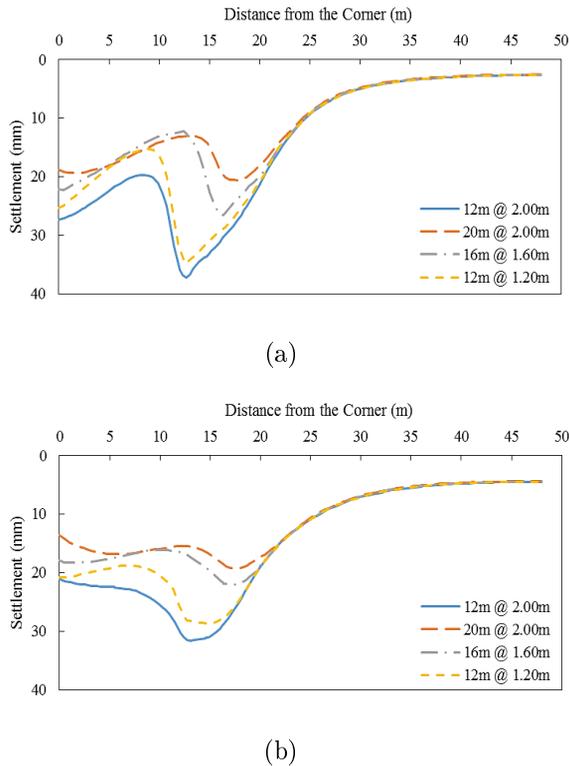
three-dimensional and two-dimensional numerical modellings for two types of soils (granular and cohesive), the following conclusions were drawn:

- The length of the zone affected by the convex corner (the zone along the wall and around the convex corner where the values of the displacements are greater than the corresponding two-dimensional values) is about 0.75 to 1 times the excavation's depth. Also, the length of affected zone in granular soil is greater than its value in cohesive soil.
- The outward three-dimensional geometry of convex corner increases the excavation-induced displacements as compared to the areas which are not near the corners. In this study, the maximum amounts of PSR (Plane Strain Ratio) are about 1.40 and 1.25 for granular and cohesive soils, re-



**Fig. 17:** Horizontal displacements of the convex corner for different reinforcing approaches (a) for sand, (b) for clay.

spectively. If there is no time, budget, or computational tools for modelling the convex corner three-dimensionally, it would be suggested to increase the amount of displacements obtained from plane strain modellings by about 50% and then compare it with allowable displacements.



**Fig. 18:** Settlements of the ground surface for different reinforcing approaches (a) for sand, (b) for clay.

- Although the horizontal soil nails are executed easier and prevent interference of nails which cross, but applying an appropriate angle over the horizon to the soil nails can reduce the wall displacements. It was found that an angle of about 10 degrees can be the most efficient.
- Applying azimuth to the soil nails in the area affected by the convex corner, significantly increases the displacements. Hence, applying azimuth to the nails is not recommended at all. The results indicate that the amount of increase in displacements is more in granular soils rather than cohesive ones.
- For reducing the displacements in the zone affected by the convex corner, increasing the soil nails length can be more effective than decreasing their horizontal spacing.

Studying the convex corners' effect on the displacements induced by anchored excavations and the effect of soil relaxation due to the partial excavation's steps in each level on the displacements can be the possible future works. To investigate the latter topic, it can be studied, for example, by comparing 3D analyses and 2D ones with different Mstage factors using PLAXIS software.

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