



Modeling and Assessing Nailing Conduct Utilizing FEM Method

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

The nailing method is utilized for temporary and permanent stabilization of the drilled excavations and walls. In most instances, nailing is much more cost-efficient than other excavation stabilization alternatives, hence the popularity and rapid development of nailing technology have been increased. In this research, several parameters such as changes in the height of the excavation, alterations in the soil environmental parameters, changes in the nails' layouts, and their lengths were analyzed to evaluate the conduct of the nailing system. The findings of this study demonstrated that each of the mentioned parameters makes changes in the locations, and the forces of the system. Further examination of the impact of each parameter, the maximum and minimum impact of the changes are assessed and ultimately, a general insight is created for designing each constituent of this study.

Keywords: Nailing; abacus software; finite element; numerical modeling.

1. INTRODUCTION

In nailed walls, vertical deformations, especially horizontal ones, are inevitable. As the height of the wall increases, so do the deformations.

These deformations have made it practically challenging to utilize this method in the vicinity of deformation-sensitive structures. If the nailed wall is not properly designed, its deformation will become excessive and more than the permitted

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level. Deformation is more significant, particularly in temporary excavations where designs are less stable, and nail lengths are shorter than permanent walls.

The design method suggested by reputable institutions (such as FHWA) for designing the nailed walls, recommends utilizing the limit balancing methods that are reasonably reliable. While this method ensures sufficient stability, it doesn't provide specific data on wall deformation. Analyzing the nailing system from various design and execution aspects can help to attain the system's optimal design, considering the effects of various parameters (nail distances, nail lengths, nail angles, etc.).

Smith and Su [1] employed the finite element method to build a 3D model for a nailed wall having a curvature plan under various conditions during the construction, service, and final loading. Then, they evaluated the conduct of the nailed wall, interaction of soil and nails, the role of reinforcement, and the mechanism of overall and internal rupture.

Zhang and Associates [2] analyzed nailed wall displacement employing a three-dimensional finite element method. Soil non-linearity, soil-nail interaction, and layer-by-layer analysis were taken into account in this model. The authors also stated that the linear stress-strain relationship is not suitable for the soil deformation analysis, since even at low stresses, soil exhibits nonlinear behavior. Hence, the nonlinear EB model proposed by Duncan and Associates (1970 and 1980) was utilized in which the soil deformation's main behavior is considered. It also assesses the use and the effect of various parameters on the conduct of the soil-nail system.

Hong et al. [3] employed a finite difference software in two dimensions to examine the effects of flexural stiffness and nail slopes on the nailed walls conduct. The soil model is a nonlinear elastoplastic one, and its stress-strain relationship is hyperbolic before submission and follows Duncan's law. It also adheres to the Mohr-Coulomb criterion in terms of yield. They also evaluated the conduct of a 7-meters-high nailed excavation in three granular soil models in the cases of a step by step drilling, nailing, and coating application, and obtained the horizontal deformation.

Sivakumar Babu et al. [4] delved into the effect of performance variables such as implementation phases, types of coatings, connections between

nails and coatings, coating hardness, and slope of the wall, conducting the numerical simulation by 2-D FLAC finite difference software. In this model, the nails are modeled by a pile element, whereas the facade cover is modeled with the beam element, where the beam element is rigidly connected to the pile element.

Mehdizadeh (2007) conducted a numerical study on the conduct of nailed walls under static loads. The numerical modeling of the construction stages of the nailed walls was carried out by the FLAC finite difference software in a 2-D environment. For modeling the soil conduct, he utilized the elastic hyperbolic model of Duncan et al. (1980) in which the nails are modeled with cable elements.

Fan and Luo [5] conducted a numerical study on the nails' layouts. They evaluated the influences of their angle and layouts on the overall stability of the nailed slope in various conditions. They also examined the nailed slope, considering the safety factor. Two-dimensional Plaxis finite element nonlinear software was utilized to perform numerical modeling of the nailed slope. Fan and Luo have also analyzed the impact of the nail layouts on the stability of the nailed slope, considering three factors including the optimal nail angle, the effect of the length, and the vertical distance of nails, on the stability of the nailed slope.

Sivakumar Babu and Singh [6] compared the conventional MC Model (Mohr-Coulomb model) for the nailed wall simulation and the two advanced soil models called HS Model (Hardening Soil Model) and HS-Small Model (Hardening Soil with Small Strain Stiffness Model). They also studied the concept of the flexural stiffness of the nails and the finite element mesh density according to the simulated results of the nailed walls. To conduct the analysis, a 10-meters-high wall was simulated in PLAXIS software, considering its plate strain conditions and the long-term behavior.

Since numerical methods can solve this specific problem, numerical modeling will be utilized [7,8]. Existing research reveals that no comprehensive study has been conducted on the deformation behavior of nailed walls and determining the optimal layout of the nailing system based on deformation criteria [9-11]. Additionally, the overhead effect of adjacent structures is very important in the level of deformation of the nailed wall, which hasn't been addressed in previous studies yet [12,13].

2. RESEARCH METHODS AND MODELING

In this study, the assessment is performed explicitly utilizing the 2D finite element software, Abaqus. Because of the nonlinear behavior of the soil due to a shear deformation, the nonlinear elastoplastic model is employed to model the behavior of soil mass.

The Abaqus software modeling included the nailed wall (three heights of 14, 20, and 26 meters) and two different modes (with and without overhead), in two dimensions and drained conditions. The overhead is equal to 50 kN/m² and 20 meters wide at the nailed wall's edge. The nails have various lengths and include angles of 15° to the horizon. After excavation of each stage and the installation of nails, a 10 cm thick shotcrete coating is applied to the excavated face. The elastoplastic soil model is nonlinear and follows the Mohr-Coulomb yield criterion. In this modeling, a layer-by-layer analysis has been carried out and following each excavation phase, the nails installed and the

coating applied. The created excavations' diameter for installing the nail is 100 mm having a 32 mm diameter metal rebar in the middle. The first and the last rows of nails are located at a distance of one meter from the top and bottom of the wall and their vertical and horizontal distances are equal to 1.5 and 2 meters, respectively which are placed in a square layout. To perform the modeling in Abaqus software, the nails are viewed as an equivalent plane element, while the nails and coating are defined as linear elasticity. Fig. 1 displays an example of the cross-section of a nailed wall having a uniform layout and overhead. Fig. 2 shows the nail cross-section. The characteristics of soil, nails, and shotcrete cover are summarized in Table 1. Therefore, for three different layouts (a), (b), and (c) and the two modes (i.e. with/without overhead), a total of 36 analyses were performed in Geoslope software to obtain the length of the nails. Then, based on the nail lengths obtained in Geoslope software, the Abaqus software is used to obtain the amount of lateral displacement of the wall in two cases (with/without overhead).

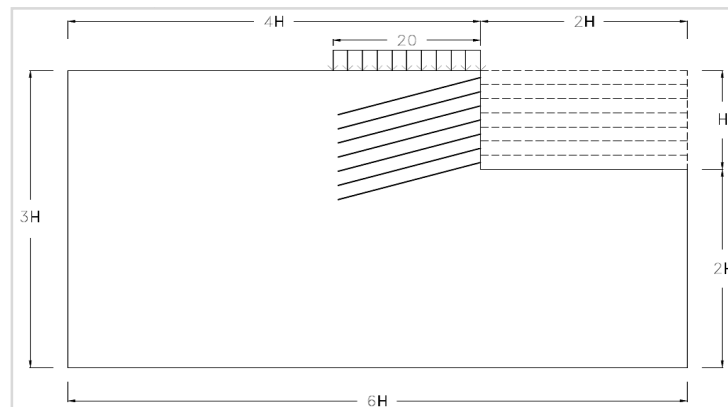


Fig. 1. Schematic of a nailed wall having the same length with overhead

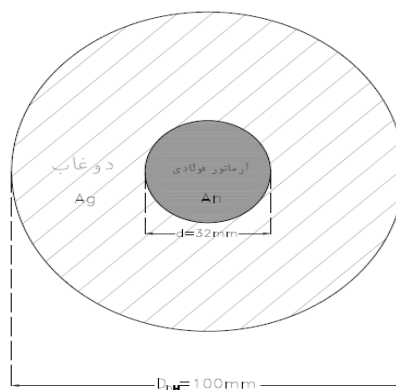


Fig. 2. Schematic of the nail cross-section

Table 1. Specifications of the soil, nails and the wall covering employed in the finite element analysis of the nailed wall

		Backfill soil	
Unit weight	γ	18.5 kN/m ³	
Young's modulus	E	70×10 ³ kPa	
Poisson's ratio	ν	0.3	
Cohesion	c	30 kPa	
Angle of internal friction	ϕ	35°	
		Shotcrete facing	
Unit weight	γ	24 kN/m ³	
Young's modulus	E	25×10 ⁶ kPa	
Axial stiffness	EA	2.5×10 ⁶ kN/m	
Bending stiffness	EI	2083.25 kN m ² /m	
Shotcrete thickness	d	0.1 m	
Poisson's ratio	ν	0.2	
Nails (Grouted diameter=100 mm)		$S_n=1.5$ m	$S_n=2$ m
Diameter of reinforcement	ϕ	32 mm	32 mm
Young's modulus of reinforcement	E_n	200 GPa	200 GPa
Young's modulus of grout (concrete)	E_g	22 GPa	22 GPa
Axial stiffness	EA	21.06×10 ⁴ kN/m	15.8×10 ⁴ kN/m
Bending stiffness	EI	131.65 kN m ² /m	98.74 kN m ² /m
Weight	w	2.17 kN/m/m	2.17 kN/m/m
Poisson's ratio	ν	0.2	0.2

3. DISCUSSION AND SIMULATION FINDINGS

3.1 Comparison of Findings with Mohr-Coulomb Model

Fig. 3 shows the wall model in Abaqus. Analyzing the 15 nodes elements, very fine mesh and boundary conditions is considered as Standard Fixities. (Vertical boundaries are shut in the vertical direction and the lower boundary of the model is shut in both directions.)

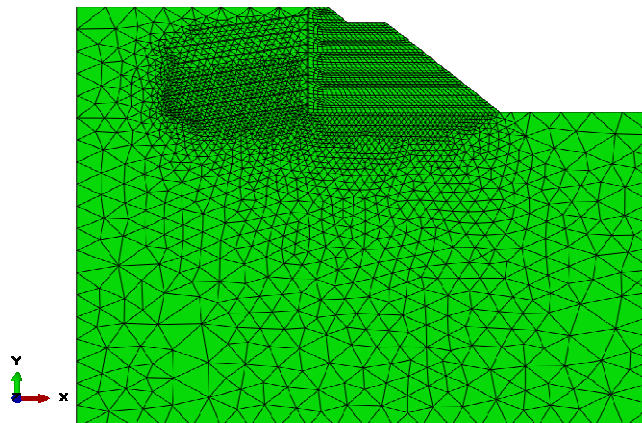


Fig. 3. Clutter wall modeling in Abaqus software

The findings regarding the displacement obtained from the finite element analysis with Mohr-Coulomb Model and the measured values of the wall in the third and fifth phases of construction are shown in Figs. 5-7.

3.2 Results Obtained in Geoslope Software

Figs. 8 displays the graphs obtained from these tables for a 14-meters-high nailed wall.

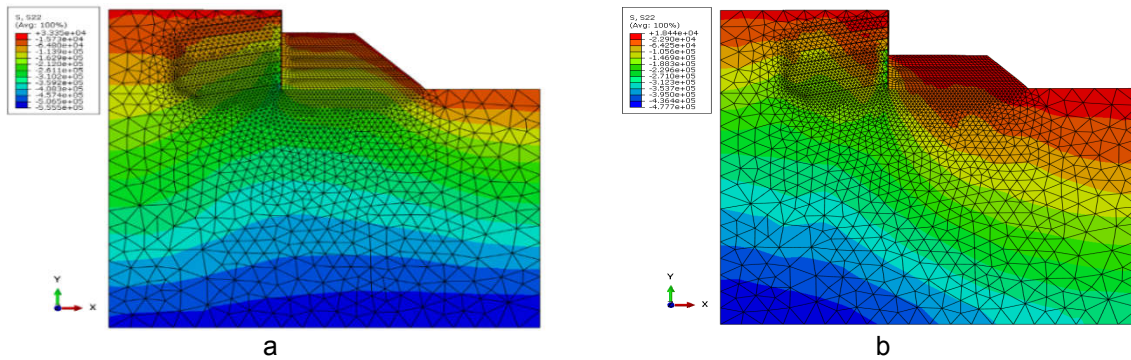


Fig. 4. a) Deformed mesh and horizontal displacement contour in the third phase, b) Deformed mesh and horizontal displacement contour in the 5th phase of the deformed mesh

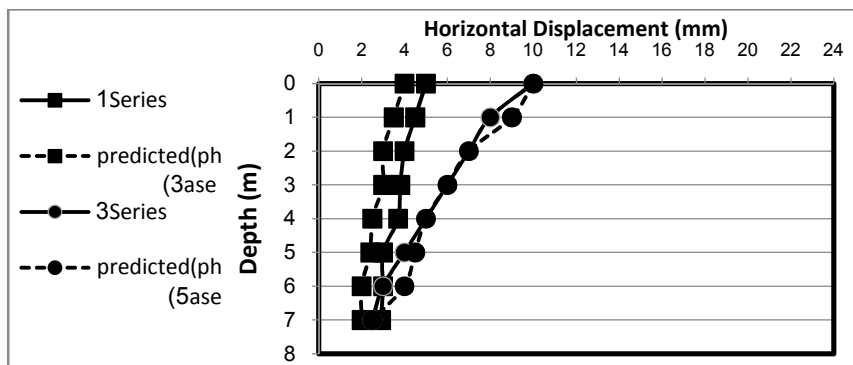


Fig. 5. Comparison of horizontal displacement values obtained from analysis at a distance of 2 meters from the façade

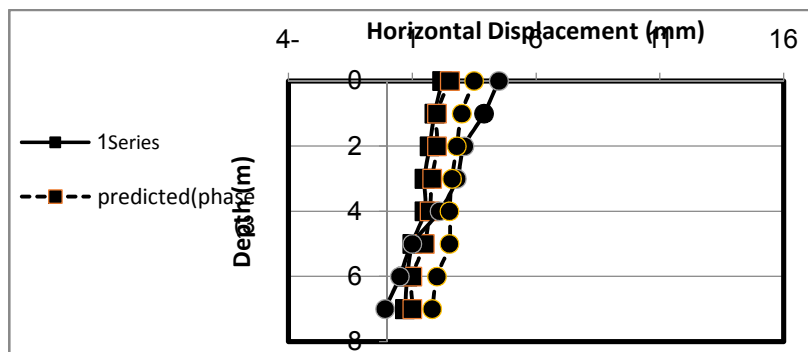


Fig. 6. Comparison of the horizontal displacement values obtained from analysis at a distance of 4 meters from the façade

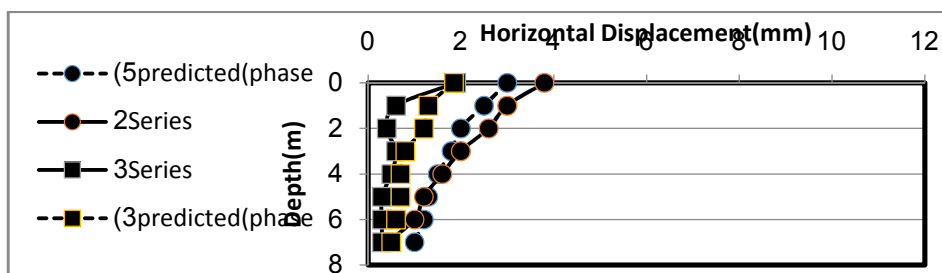


Fig. 7. Comparison of horizontal displacement values obtained from analysis at a distance of 8 meters from the façade

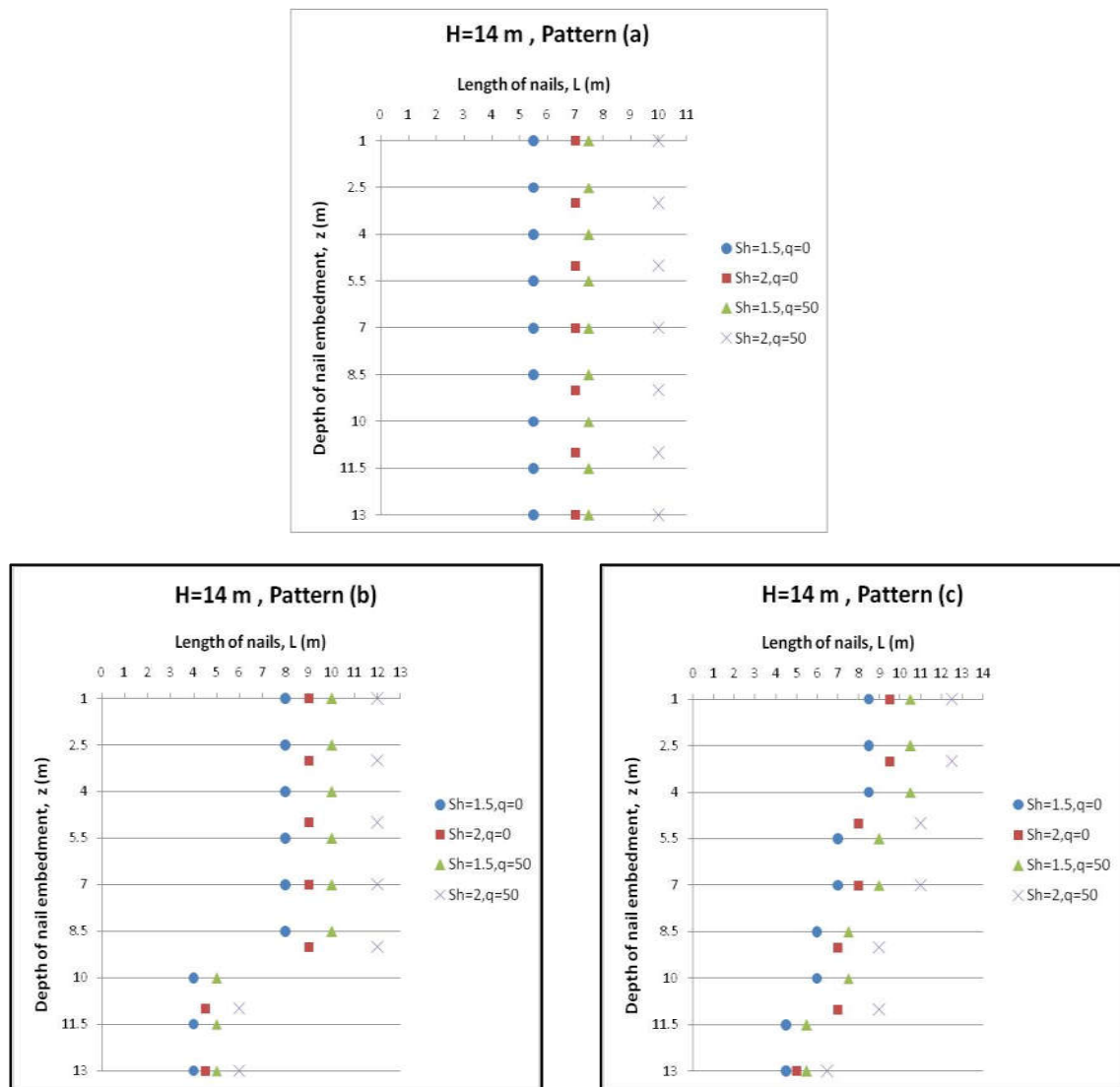


Fig. 8. Length of the nails obtained for a 14-meters-height wall and layout (a), (b) and (c)

3.3 Results Obtained from Abaqus Software

Tables 2-4 and Figs. 9-11 reveal the δ / H values obtained from the finite element analysis for layout (a), (b), and (c) and nail distances of 1.5 and 2 meters. As alluded to in

Chapter 2, FHWA regulations state that horizontal deformations which are larger than $0.005H$ during the implementation are not ideal. As can be seen from the following figures and tables, the layout (a), that is the utilization of uniform length nails is not suitable for nailed walls.

Table 2. δ / H Values for layout (a)

		$S_h=1.5$	$S_h=2$
q=0	δ/H (H=14)	0.00033	0.0004
	δ/H (H=20)	0.0006	0.0008
	δ/H (H=26)	0.0006	0.0008
pattern (a): (uniform)			
q=50	δ/H (H=14)	0.0006	0.0007
	δ/H (H=20)	0.001	0.0013
	δ/H (H=26)	0.0012	0.0014

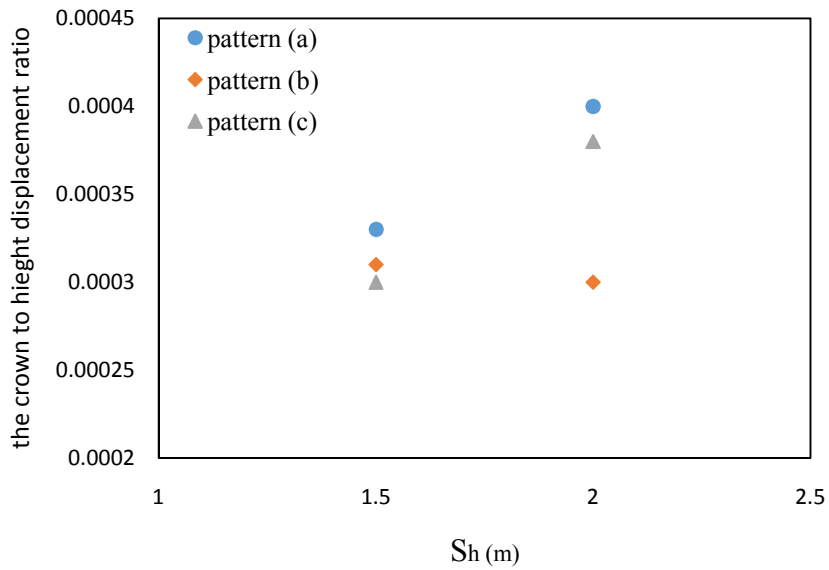


Fig. 9. δ/H values for the excavation of a 14-meters-hieght and zero overhead

Table 3. δ/H values for layout (b)

		$S_h=1.5$	$S_h=2$
q=0	δ/H (H=14)	0.00031	0.0003
	δ/H (H=20)	0.0004	0.0007
	δ/H (H=26)	0.0005	0.0008
pattern (b)			
q=50	δ/H (H=14)	0.0005	0.0007
	δ/H (H=20)	0.001	0.00115
	δ/H (H=26)	0.0011	0.0012

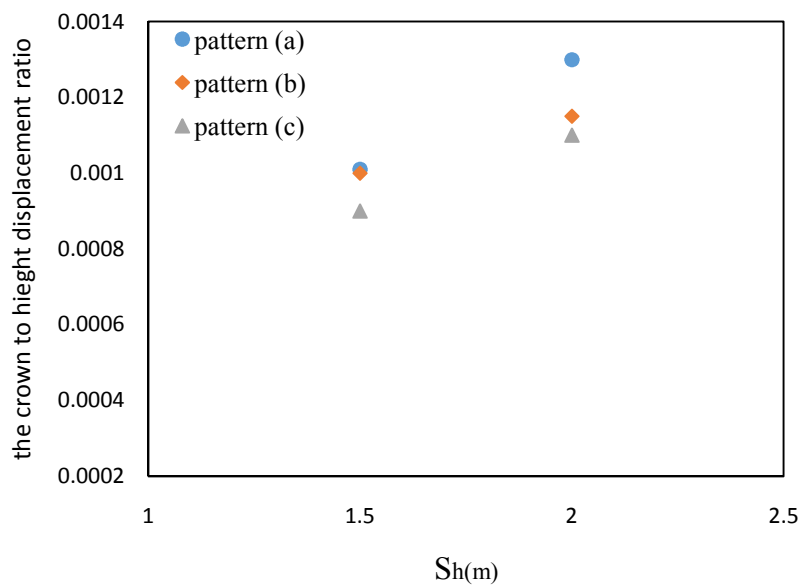


Fig. 10. δ/H values for the excavation of a 20-meters-height and a load of 50 kPa

Table 4. δ/H values for layout (c)

		$S_n=1.5$	$S_n=2$
q=0	δ/H (H=14)	0.0003	0.0004
	δ/H (H=20)	0.0003	0.0007
	δ/H (H=26)	0.0005	0.0007
pattern (c)			
q=50	δ/H (H=14)	0.0003	0.0006
	δ/H (H=20)	0.0009	0.0011
	δ/H (H=26)	0.0011	0.0011

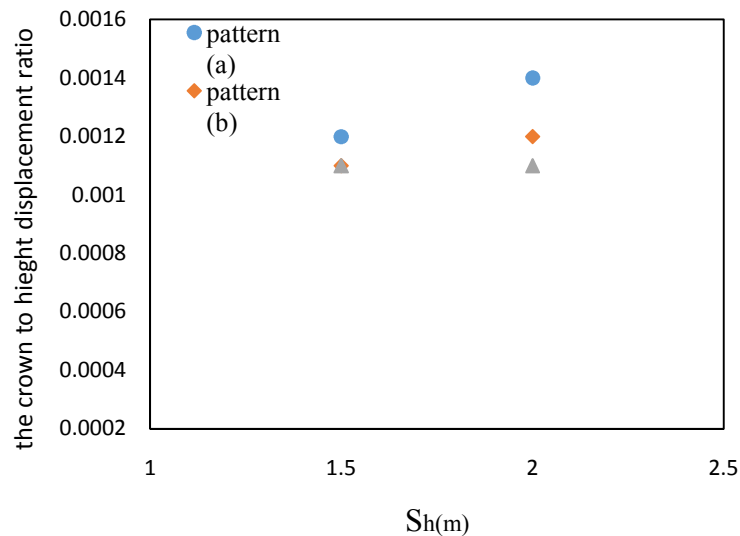


Fig. 11. δ/H values for the excavation of 26-meters-height and an overhead of 50 kPa

3.3.1 Examination of the effects of angle of the nails' placement relative to the horizon

Modeling was done for a 20-meters-deep excavation, two groups of nails with equal length in height (lengths of 10 and 16 meters) were carried out.

The overhead used here was 20 kPa. According to Fig. 12, the findings demonstrate that increasing the angle of the nails' placement relative to the horizon, shotcrete wall crown's horizontal displacement increases 15% for the 10-meters-nail and 10% for the 16-meters-nail. As can be seen, in the angles of greater than 15 degrees, decreasing effects are witnessed in the safety factor. Hence, a 15 degrees nail angle is chosen for further calculations.

As can be seen in Fig. 13, the modeling was conducted at zero, 20 kPa, 50 kPa, and 100 kPa overheads and a 15 degrees horizon angle. As

shown in the diagrams, as overhead increases, the horizontal displacement of the crown increases and the safety factor decreases, as can be expected. Moreover, as can be seen from the figures, there exists a slight influence of the nails' length on the crown horizontal displacement at low overheads, so that increasing the overhead, the influences of the nail length reveal.

Furthermore, the amount of horizontal displacement against the excavation steps for different angles of the nail is plotted in Fig. 14. As can be seen from this diagram, the effect of the angle of the nail placement relative to the horizon surface in the early stages of excavation is negligible, but with an increase in the excavation phases, the effect of changing the angle of their placement relative to the horizon surface is manifested in the horizontal displacement decrease, so that in a 20-meters-deep pit, changing the angle from 5 to 25 degrees increases the horizontal displacement by 10%.

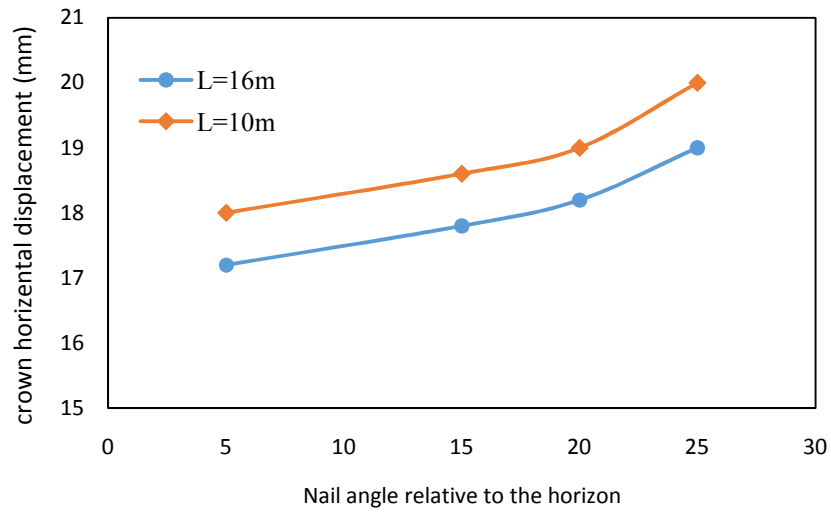


Fig. 12. Horizontal displacement of the nailed wall crown and the safety factor for the variable nail angle and a 20 kPa overhead

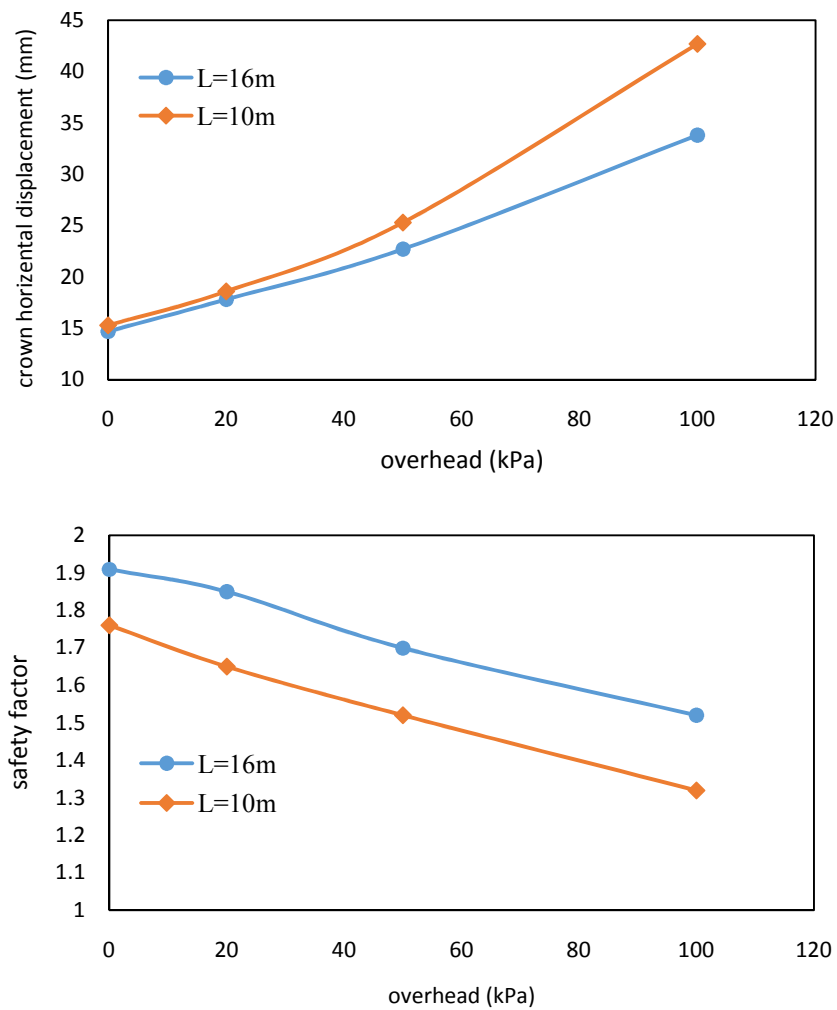


Fig. 13. Horizontal displacement of the nailed wall crown and the safety factor for variable overheads

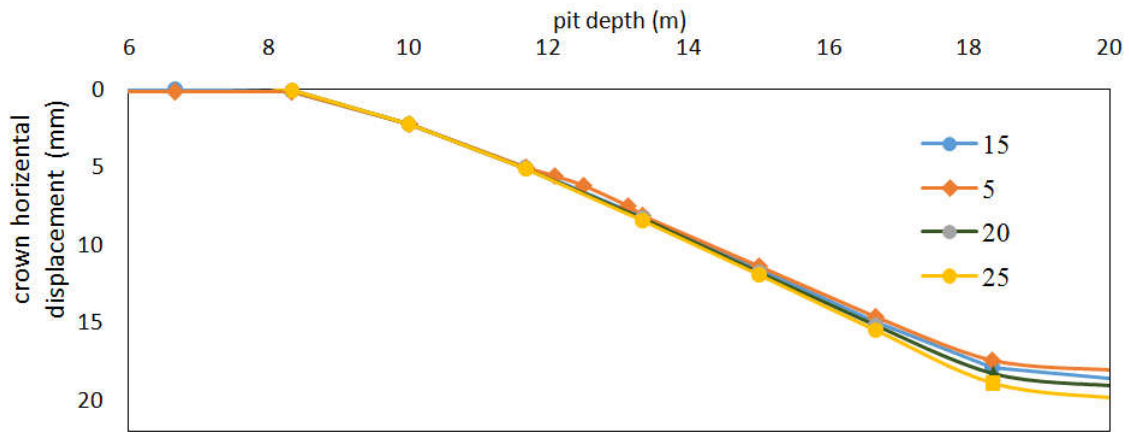


Fig. 14. Horizontal displacement vs. excavation phases at variable nail angles and a 20 kPa overhead

3.3.2 Evaluation of the effects of the soil environment parameters

The conduct of the nailed wall system is analyzed via alterations in the environmental

parameters of soil such as the soil adhesion, the soil elasticity module, as well as the overhead applied to the excavation. According to the results shown in Fig. 15, increasing the soil adhesion from 10 to 50 kPa leads to a decrease

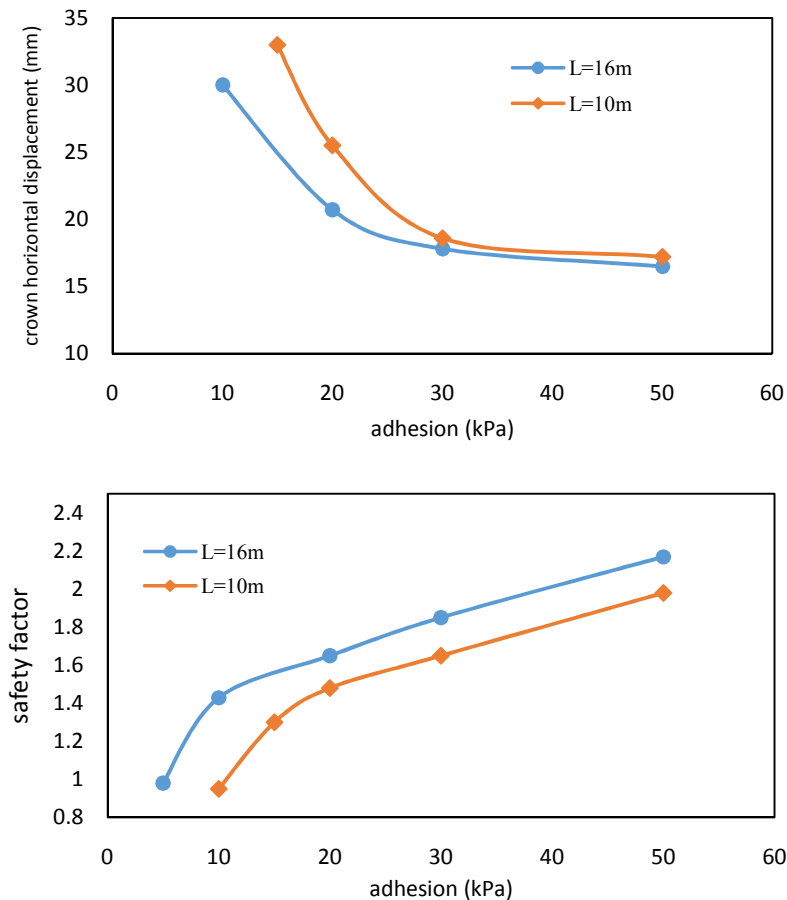


Fig. 15. Horizontal displacement of the nailed wall crown and the safety factor vs. changes in the soil adhesion

in horizontal displacement which is greater for the nails having a shorter length, which is about 100%. The figure also shows a very significant increase in the safety factor. The significance of adhesion in the nailing method cannot be left unmentioned. As can be seen in these diagrams, for adhesions smaller than 20 kPa, the horizontal displacement of the crown significantly increases and the safety factor significantly reduces. These results indicate the low applicability of the nailing method in low adhesion soils.

Furthermore, as can be seen in Fig. 16, increasing the elastic module of the soil from 10 MPa to 100 MPa for a 20-meter-depth excavation, the safety factor of both nails is almost doubled. Its impact on the crown's horizontal displacement is also significant, but

there is not much difference between the different nail lengths, especially in larger elastic modules.

3.3.3 Examining the impact of excavation angle

The change level in the displacement of the wall crown and the safety factor of the wall is plotted for the angle of vertical inclination of the excavation. If there exists no overhead, the safety factor against the stability of the excavation is higher than the overhead, which is most at the excavation angle of 85 degrees, that is evident. According to Fig. 17, the horizontal displacement of the crown of the nailed wall also displays a reduction of about 50% in overhead.

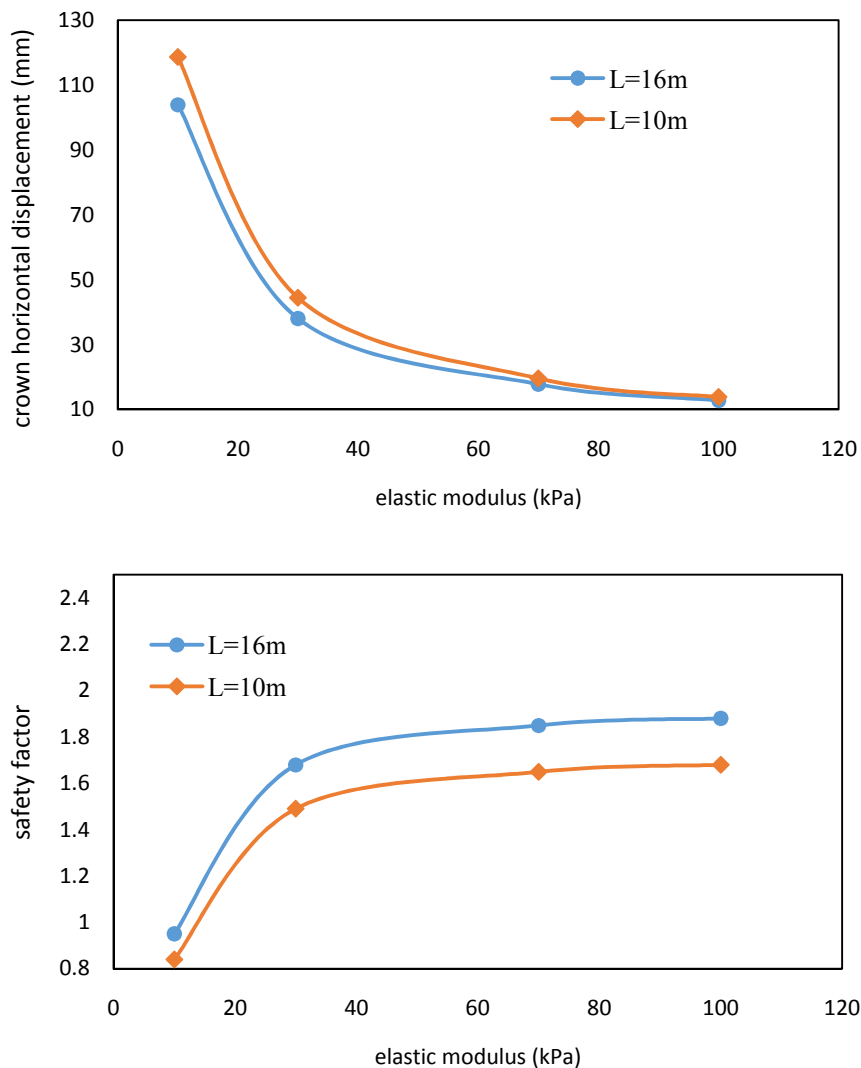


Fig. 16. Horizontal displacement of the nailed wall crown and the safety factor vs. changes in the soil elastic modulus

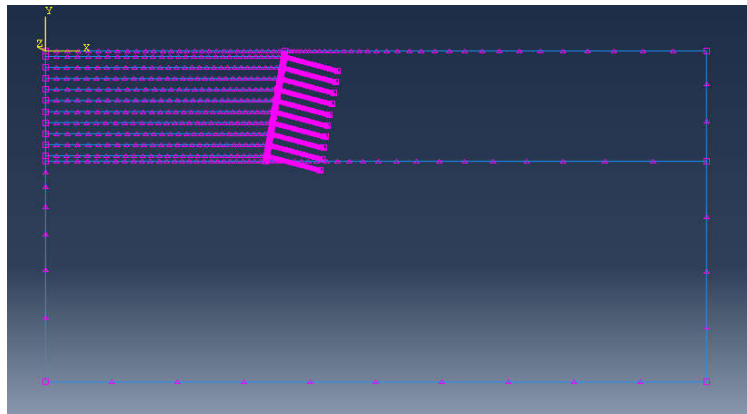


Fig. 17. the built model for the wall with a 80-degree relative to the horizon

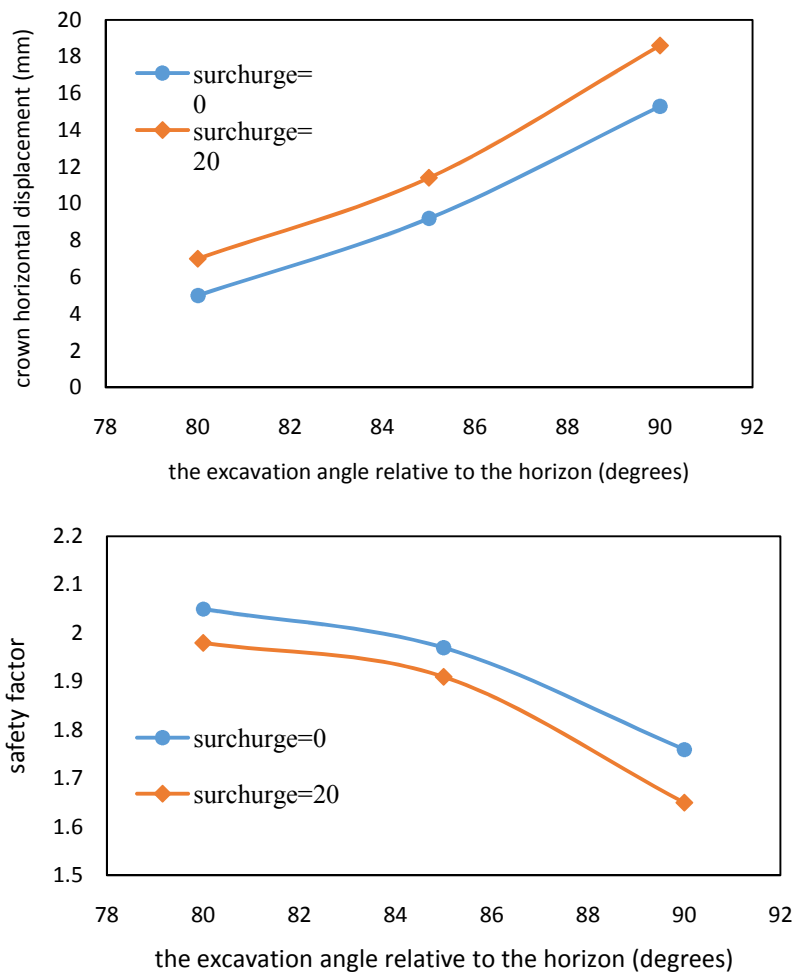


Fig. 18. Horizontal displacement of the nailed wall crown and the safety factor vs. changes in the excavation angle at 20 kPa and with no overhead

Horizontal displacement in various excavation stages by changing excavation angle from 90 to 80 degrees is shown in Fig. 19 for a 10-meters-length nail having a 15 degrees angle relative to the horizon. Its impact will be disclosed in the excavation's middle and later stages. At a depth

of 10 meters, the effect of the changes in the excavation angle on horizontal displacement begins to be evaluated. And after this depth, the rate of change is greatly affected by reducing the excavation angle relative to the vertical direction, so that at a depth of 20 meters, by reducing the

excavation angle from 90 to 80 degrees, the horizontal displacement rate is reduced by about 60%.

3.3.4 Examining the impact of increasing excavation depth

In this section, the impact of excavation depth on the overall performance of the nailed structure in terms of stability and displacement is analyzed. As shown in Fig. 20, by increasing excavation depth and assuming that the nail length to the depth of the excavation is constant, the rate of horizontal displacement of the crown of the shotcrete wall is significant. For deep excavation, the appropriate length of the nailing is much more significant. The safety factor against the stability of the excavation also increases by growing the depth of the excavation, assuming that the nail length to height decreases for all three excavation depth.

Increasing the overhead, the decrease has a sharper slope.

Given a ratio of 1 to 2 for the nail to the excavation depth ratio, the overhead effect is much more effective at a depth of 14 meters than a depth of 20 and 26 meters.

Generally speaking, increasing excavation depth, the overhead impact decreases due to the formation of wedge rupture on a larger scale, which has a lower influence on the overhead. Trends of conduct in these conditions can be seen in Fig. 21. As evident in this figure, the overhead effects on the safety factor are the same for the depths of 20 and 26 meters. As well, the displacements difference for the 20- and 26-meters excavation crowns is less than the displacement difference for the 20- and 14-meters ones, which reveals a decrease in the overhead impact of in deep excavations.

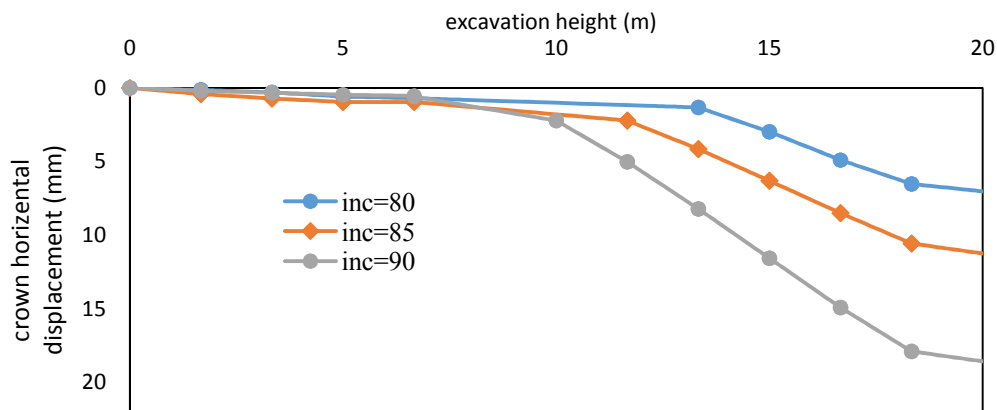
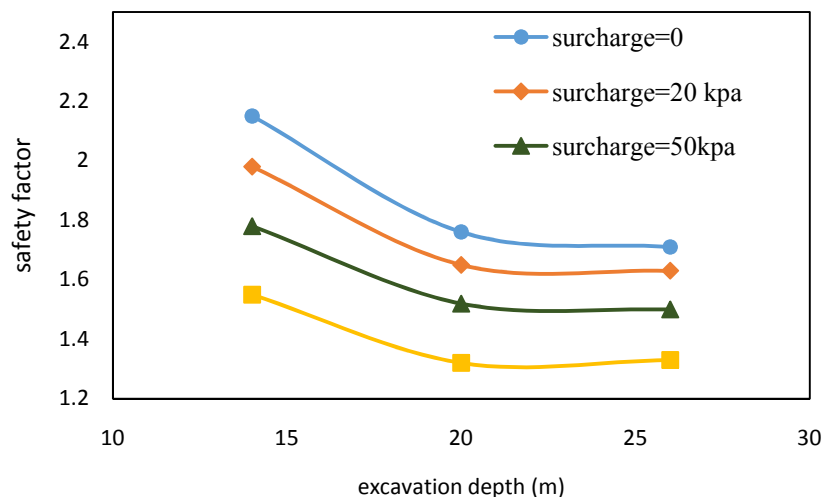


Fig. 19. Horizontal displacement of the nailed wall crown at various stages of excavation at 20 kPa overhead



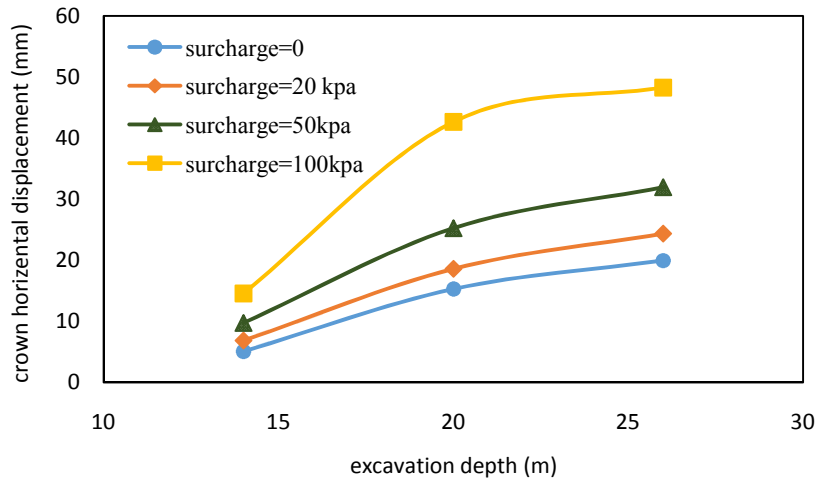


Fig. 20. Horizontal displacement of the nailed wall crown and the safety factor for the excavation depth

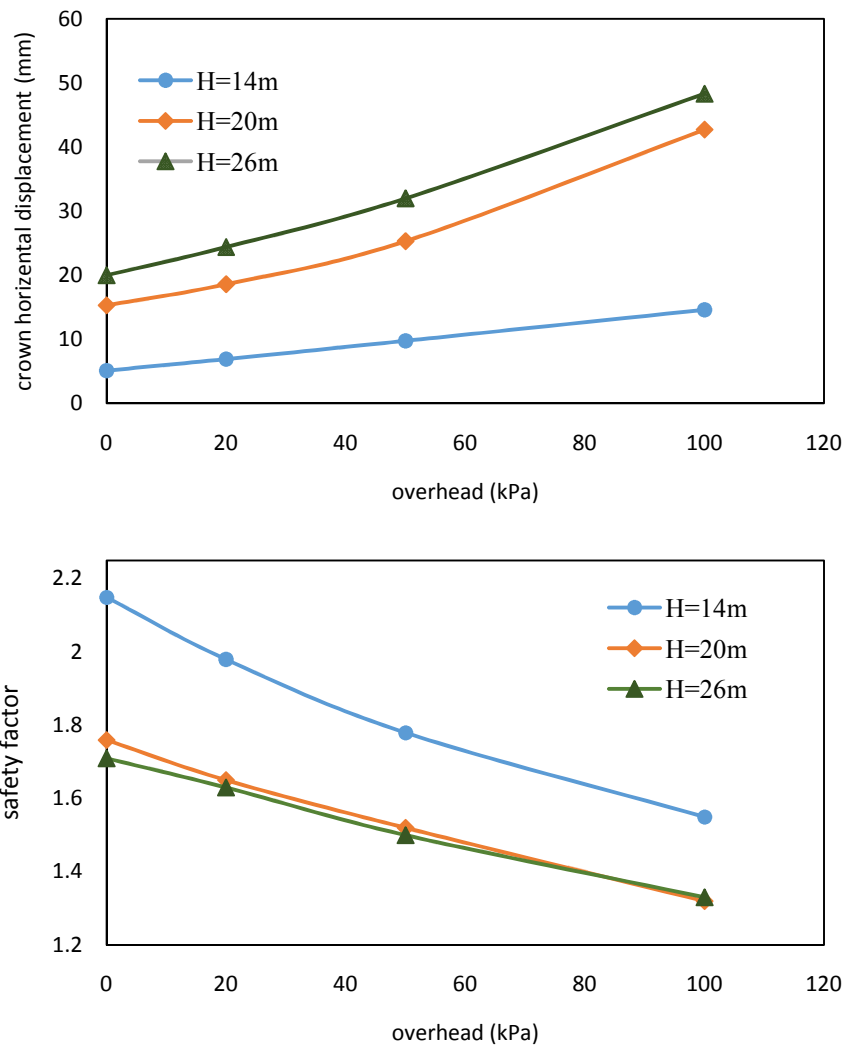


Fig. 21. Horizontal displacement of the nailed wall crown and the safety factor in variable overheads

4. CONCLUSION

In this research, a parametric study has been carried out to investigate the influences of the nails in an excavation wall stabilization. First, we modeled a nailing system in the software. The obtained results from the clutter wall accurate tooling project have been compared with the same excavation modeling results to validate the software. Next, we evaluated the influences of the excavation stabilizing nailing system, and the horizontal displacements of the nailed crown wall, as well as the safety factor against the excavation stability in various depths. Then, we studied the effects of various parameters such as the nail angle relative to the horizon, the soil specifications, the excavation angle, and the pile effects on excavation.

- The overhead of a lower depth excavation has the most influence on the safety factor against the excavation stability and the horizontal displacement of the nailed wall. The horizontal displacement of the wall was evaluated for 3 various layouts. The findings show that the displacement to the height ratio is not suitable for a constant length layout.
- The nail placement angle relative to the horizon is considered a very important parameter. In this study, the optimal angle is considered 15 degrees for increasing the safety factor against stability. As well, the research results indicate that the closer the nail angle to the horizon, the lower the crown horizontal displacement of the nailed wall will be.
- The results also show the important role that the soil elastic modulus and the soil cohesion play in the parameters such as the horizontal displacement of the nailed wall and the safety factor against the excavation stability.
- The excavation angle plays a critical role in reducing the horizontal displacement of the nailed wall and increasing the safety factor. If the shop space allows one to excavate with an angle other than 90 degrees, it is considered a suitable method for safe excavation.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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