

Numerical Simulation of Ground Anchor-Soil Nail Retaining Systems for Academic-Learning Purposes

Kamran Panaghi *

Department of Civil and Architectural Engineering, School of Science and Engineering, University of Kurdistan Hewlêr, Erbil, Kurdistan Region, Iraq

kamran.panaghi@ukh.edu.krd

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Abstract

The ever-expanding urban architecture in developing areas requires more land space for construction purposes to be available. For this, utilizing the sub-surface areas through excavations in populous cities is now on the increasing trend. Two major concerns in such excavation projects are excavation-wall stability and the induced ground settlements which can be countered by a soil nailing-ground anchor system. In this regard, influential factors such as nail length and nail inclination angles can affect the overall performance of stabilized ground. Therefore, the focus of the present study is on how the aforementioned influence excavation-induced ground deformations. The numerical simulation is conducted using the software Plaxis 2D. The established numerical models help to explain how changes in the nails' inclination angles and anchor lengths can change the observed behavior of the walls; from which helpful tips for practicing engineers are drawn accordingly. Such results could also be utilized for classroom presentations to aid students' understanding of geotechnical engineering concepts.

Keywords: Numerical Simulation, Soil Nailing, Hardening Soil Model (HS), Fontainebleau Sand, Plaxis 2D.

1. Introduction

The construction procedure in large metropolitan areas and developing cities mandate more use of the land available. Since large structures such as skyscrapers and tall buildings would usually have foundations buried deep under the ground, the safe excavation of the surface soil is a significant part of these projects. This is mainly due to the lateral ground deformations and the settlements that occur as the outcome of these practices (Dong et al., 2014; Hsiung, 2009; Hwang et al., 2007; Konda et al., 2008; Liu et al., 2005). Therefore, the implementation of proper engineering standards and professional practice through appropriate measures to counter unfavorable outcome in the excavation procedure is a must. For this, different retaining systems such as pile walls, sheet pile walls, and soil nail walls are developed to control ground deformations in practice. Since the choice of the most suitable retaining system is project-specific, only apt engineering judgement would determine the design at last. However, economic considerations in every project would also play an important role in the decision-making processes. Eventually, engineers opt for a design that meets both safety and economy criteria. One of the most economically-viable options within the soil-retention techniques is soil nailing (Watkins and Powell, 1992). Soil nails are passive reinforcing elements that are inserted into the soil or soft rock and then grouted for further bonding with the surrounding domain (FHWA, 2015). The soil nails are sometimes combined with post-tensioned members to boost the overall performance of the retention system. These prestressed members are

referred to as the tie-backs or ground anchors which comprise an active retaining system. The main purpose of such systems is to transfer tensile loads from the nails to the ground (FHWA, 1999). Since this technique eliminates the need to shore up the excavated wall, the work area will be clear of obstructions such as struts or any transverse elements. As a result, faster completion of the project in comparison to other techniques is quite feasible.

The conventional tools available for the design of soil nailed walls with anchor systems are based on the limit equilibrium method that can only capture the failure state of the structure (Barret et al., 2013). In this regard, some work has also been conducted to account for the interaction between the structural elements and the surrounding soil (e.g., Feijo and Erhlich, 2003; Pradhan et al., 2006). One group of techniques employed for the analyses concerning excavation-induced ground deformations include the empirical or semi-empirical methods (Clough and O'Rourke, 1990; Wong et al., 1997; Ng, 1998; Long, 2001; Moormann, 2004; Zhang et al., 2018). These methods arise from the fact that the purely mathematical approaches for practical applications in such problems are too complicated. Another alternative for a deep excavation problem is the numerical analysis method that enables the behavioral assessment of both structural elements and geotechnical domain under different loading, groundwater, and construction sequence conditions in projects (Hsieh and Ou, 1998; Yang and Drumm, 2000; Zhou et al., 2009; Khoiri and Ou, 2013; Likitlersuang, 2013; Garg et al., 2014; Nguyen and Treysse, 2015; Shi et al., 2015; Orazalin et al., 2015; Hsiung et al., 2018).

Since the construction of soil-nailed structures are performed in stages, it can be deduced that the numerical tools available to tackle such problems are of profound importance for cost-effective analyses in projects. Consequently, engineers usually resort to numerical simulation studies that facilitate modeling investigations. For the current study, the developed numerical model was first validated by comparing its results with those of Wang et al. (2016) study. Following this, the 2D model of a vertical excavation wall was established and the variations of anchor length and drilling angle in the wall were modelled. The output results were then scrutinized and discussions on the effects of these factors on the overall system response were conducted. The results obtained in this work confirm the recommendations made in the available literature which are derived from monitoring observations and experimental or numerical investigations.

2. Numerical Simulation Procedure

2.1 Numerical Model

The software employed for the numerical simulation analyses is PLAXIS 2D V21.01 (2021) which is based on the finite element method for solving the partial differential equations in the study domain. Plane strain analysis is adopted for the numerical modeling of the excavation procedure. The sides of the soil domain are restrained in the horizontal direction only while pin supports are used for the bottom boundary. 15-node triangular elements are used in the meshing of the domain and no groundwater effects are considered for the depth of excavation.

2.2 Model Geometry

The geometric properties of the excavation model are chosen so that model geometry did not affect the accuracy of the results (Briaud and Lim, 1997). The height of the excavated wall is 10 m and the wall is nailed to the soil with 6-m nails. The first two nails are inserted into the ground after two 0.5-m excavation intervals. Other nails are then inserted at depth intervals of 1 m. All of the nails have a diameter of 36 mm and the ones located below the depth of 3 m in the wall are anchored to the ground using prestressed embedded beam elements. Figure 1 shows a schematic diagram of a soil retention system consisting of shotcrete wall, soil nails, and ground anchors. The specific geometry used in the current investigation is also depicted in the figure.

All the anchored nails are subjected to a prestressing force of 250 kN/m and the diameter of grouted anchorage in all cases is chosen as 30 cm. Three anchor lengths of 1, 2, and 3 m and four cases of drilling angles of 0, 5, 10, and 15 degrees are considered for the nailing system in this study to simulate real-world practices. A spacing of 1 m is considered for all the nails in the model which resulted in a square pattern for the anchored nails. Except for the two uppermost nails that are inserted at 0.5-m depth intervals, all other nails are placed at 1-m intervals throughout the depth of excavation. The first nail is anchored at the depth of 3 m in accordance with FHWA (1999) recommendation on the depth for the soil in front of the top anchor's bond zone. This is to prevent ground failure due to pullout forces. Additionally, the shotcrete wall thickness is 20 cm. Table 1 summarizes the geometrical and material properties of structural elements used in the numerical model.

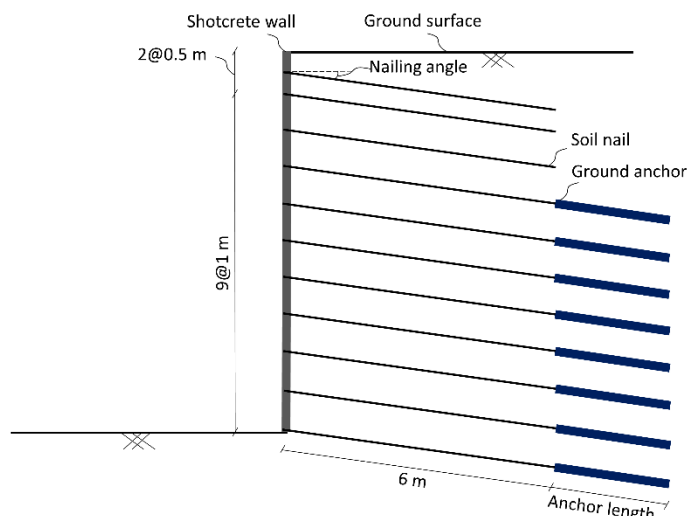


Figure 1. Schematic Representation of a Soil-Nailed Wall in The Current Study Comprised of a Shotcrete Wall, Nails, and Anchors.

Table 1. Material Properties of The Structural Components of The Soil-Nailed Wall in This Study.

Structural member	Parameter	Unit	Value
Shotcrete wall	Material behavior: Elastic		
	Young's modulus (E)	GPa	21
	Thickness (t)	cm	20
	Poisson's ratio (ν)	-	0.2
Nails	Material behavior: Elastic		
	Young's modulus (E)	GPa	210
	Diameter (d)	mm	36
	Drilling angle	°	0, 5, 10, 15
	Spacing (L)	m	1
Anchors	Material behavior: Elastic		
	Young's modulus (E)	GPa	20
	Unit weight (γ)	kN/m ³	24
	Diameter (d)	cm	30
	Length	m	1, 2, 3
	Spacing (L)	m	1
	Axial skin resistance	kN/m	250

3 Soil Model and Soil Properties

The constitutive relationship in modeling soil behavior is of profound importance for obtaining accurate results. While many such models are available, the choice of the most suitable behavioral law is largely dependent on the problem studied. For the current investigation, the Hardening Soil (HS) model is used to characterize soil stress-strain relationship. The distinguishing feature of this model is that it is capable of modeling both soft and stiff soil behavior (Schanz, 1998). Since the plastic deformations in soil start from the early stages of loading, a hardening rule must be applied after the initial yielding in soil in order to better capture deformations (Plaxis, 2021). This rule ensures a stress-dependent stiffness for soil which is imposed through the input parameter (m) in a power law. The value of the power parameter in this study is assumed as 0.5 based on the earlier investigation by which this study is validated. It is worth mentioning that this parameter usually takes values between 0.5 and 1 with 0.5 as being suitable for sand. The HS model is superior to the hyperbolic model by Duncan and Chang (1970) as it uses theory of plasticity and a cap for the volumetric component of the yield surface for drained soil during triaxial tests. Additionally, the rule accommodates soil dilatancy as a factor that

affects its behavior. The input parameters for this model include the plastic straining due to primary deviatoric (E_{50}^{ref}) and compression (E_{oed}^{ref}) loadings, elastic unloading/reloading stiffness (E_{ur}^{ref}) and Poisson's ratio (ν_{ur}), cohesion (c), friction angle (φ), and dilation angle (ψ).

The soil type used in the current study is Fontainebleau sand which is a well-sorted clean sand with particle diameters ranging from 0.063 mm to 0.25 mm (Latini and Zania, 2017). The HS parameters for the soil are chosen as those used in Sheil and McCabe (2016). Table 2 presents the Fontainebleau sand data employed in the current study.

Table 2. Fontainebleau Sand Properties Used in The Simulations.

Soil type	Parameter	Unit	Value
Fontainebleau sand	Unsaturated unit weight (γ_{unsat})	kN/m ³	16.5
	Saturated unit weight (γ_{sat})	kN/m ³	18.5
	Minimum void ratio (e_{min})	-	0.54
	Maximum void ratio (e_{max})	-	0.865
	Deviatoric loading stiffness (E_{50}^{ref})	kN/m ²	18e3
	Compression loading stiffness (E_{oed}^{ref})	kN/m ²	18e3
	Unloading/reloading stiffness (E_{ur}^{ref})	kN/m ²	45e3
	Power (m)	-	0.5
	Cohesion (c)	kN/m ²	3
	Friction angle (φ)	°	38
	Dilation angle (ψ)	°	8
	Poisson's ratio (ν_{ur})	-	0.3

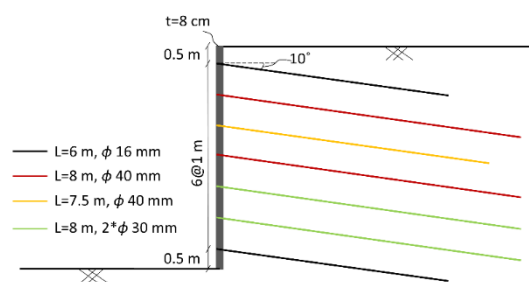
The critical depth of excavation for unsupported ground can be calculated from the following relationship (Das and Sobhan, 2014):

$$h_c = \frac{2c}{\gamma K_a}$$

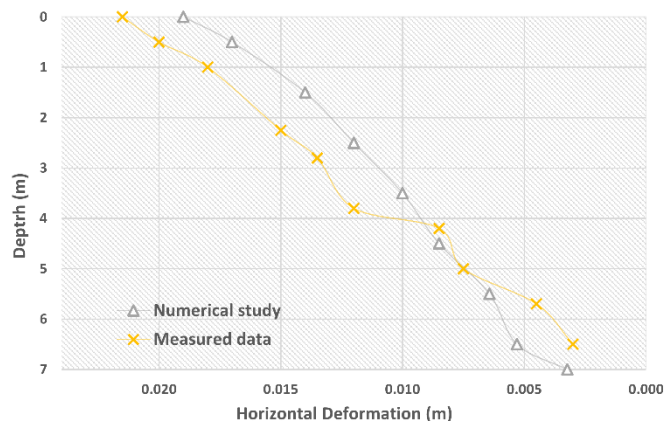
in which h_c and K_a stand for the critical depth and Rankine's active earth pressure coefficient, respectively. Considering the aforementioned in combination with a safety factor of 3 against ground failure, the unsupported depth for the excavated ground in the current study was obtained as 1.5 m. However, the first two layers of the excavated soil were limited to 0.5 m for limiting the ground deformation at the beginning stages of excavation.

4 Model Validation

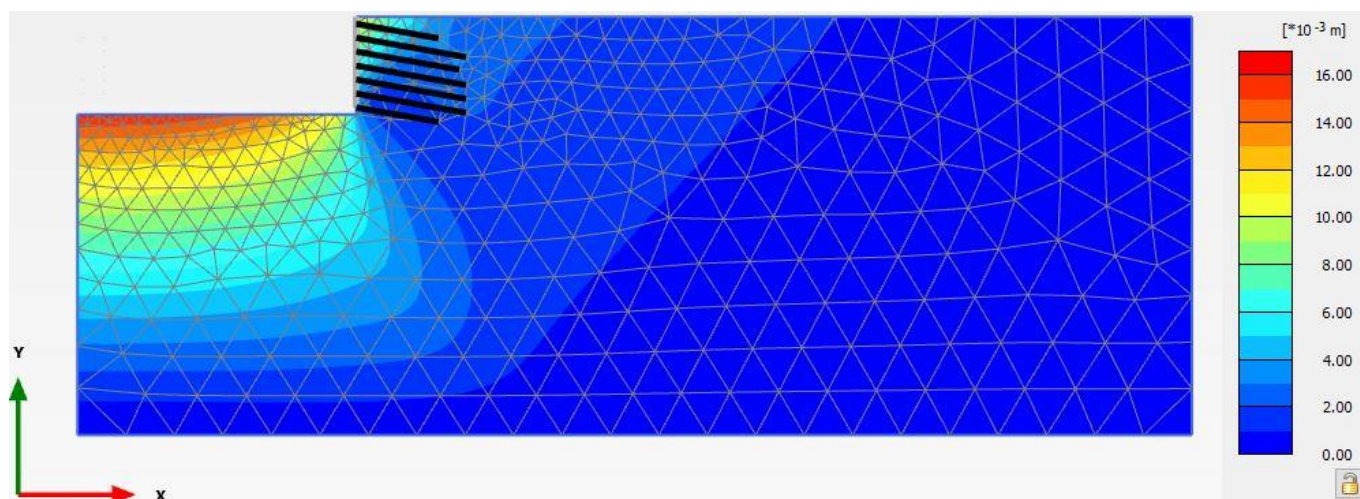
The established numerical model was validated using the data obtained from CLOUTERRE project that was a national soil nailing research program in France throughout the years 1986-1990 (Plumelle and Schlosser, 1990). The soil type on site consisted of Fontainebleau sand with a uniform gradation. For the current study, a case study within the aforementioned project was chosen for the purpose of validating the numerical model. The wall in the chosen study had a height of 7 m with nails inserted at every 1 m and 1.15 m distances in the vertical and horizontal directions, respectively. However, the first nail was placed into the ground after a 0.5 m-thick soil layer was removed. The arrangement of the nails and their properties were selected so that no possibility of nail pullout existed. The nails had three different lengths of 6, 7.5, and 8 m with 16, 30, and 40 mm diameters. All the nails were inserted into the ground with an inclination angle of 10° with respect to the horizontal. The facing wall had a thickness of 8 cm and was constructed using shotcrete technology. Figure 2(a) shows details concerning model geometry and nailing configuration in one case study of the CLOUTERRE project. The results obtained from the numerical simulation study were compared with the measurement data from the project and a generally good agreement between the results was observed (Figure 2(b)). The software output plot illustrating variations in ground deformation within the domain is presented in Figure 2(c).



a)



b)



c)

Figure 2. a) The CLOUTERRE Project Case Study Characteristics Used for The Validation of The Current Study, b) Comparison of The Numerical Analysis Results With The Reported Data of The Project, and c) Ground Deformation Plot Illustrating Deformation Values Throughout The Domain.

5 Results and Discussion

The numerical simulation analyses were conducted for the 10 m-wall using different drilling angles for the nails in combination with three different anchor lengths. The nail inclination angles in the study were 0, 5, 10, and 15 degrees from the horizontal direction which were considered for cases with 1, 2, and 3 m-long anchors. No surcharge loading was assumed in the computations and the ground water effects were ignored. Figure 3 illustrates the deformed facing wall and ground surface after running the model for the case of 1 m anchor length with an angle of 10 degrees with the horizontal.

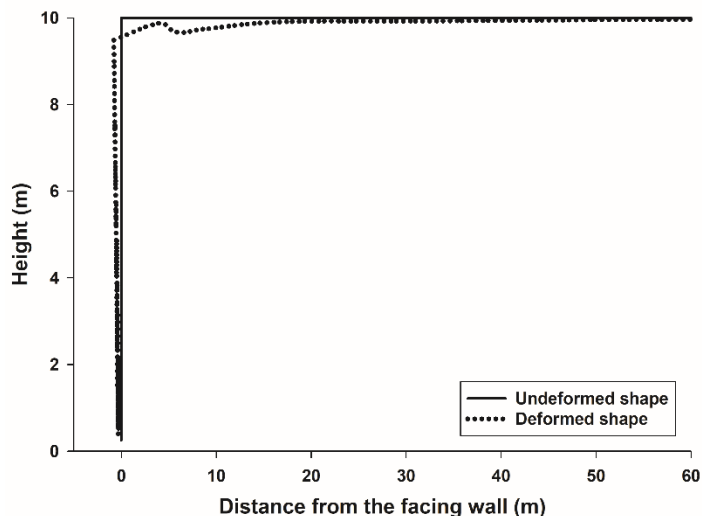


Figure 3. The Deformed and Un-Deformed Graphs of The Facing Wall and Ground Surface for The Nailing System With The Inclination Angle of 10 Degrees and 1 m of Anchoring.

The horizontal deformations of the wall and the accompanying ground settlements are significant factors in assessing the success of a completed project. Excess wall deformations are not only aesthetically unfavorable, but they could also pose serious hazards in populous urban areas. Furthermore, it is necessary for the vertical deformations in the immediate vicinity of the excavated ground to be limited so that no interruption in the services provided by infrastructure such as roads, buildings, and pipelines would materialize.

6 Drilling Angle and Anchor Length Variations

The effects of anchor length and drilling angle variations on the horizontal wall deformations and ground settlements were considered in this section. Figure 4 shows wall deformation graphs for different anchor lengths and nailing inclinations. The wall deformation magnitudes were observed to have a decreasing trend from stem to toe. Additionally, the deformations decreased with anchor length in all cases. These trends were found to be true for all cases regardless of the drilling angle of nails. Further investigation into the results revealed that the inclination angle of the nailing system is a factor in the amount of the deformations endured by the shotcrete wall (Figure 5). The wall deformations for the nailing system with no inclination with respect to the horizontal were the least and the values increased with nailing angle. Therefore, the most efficient drilling orientation for the nails is perpendicular to the wall (horizontal direction). However, practical limitations for drilling equipment and the favorable influence of gravity for grouting in the holes has rendered the nailing operation to be usually inclined at angles of 10 or 15 degrees with the horizontal.

Figure 6 shows the ground settlement profiles for different cases of anchor lengths within one drilling angle for each graph. It is noted that the effect of anchor length in reducing vertical deformations is significant for the first 15 m of distance from the facing wall. The longer anchors will render smaller ground settlements due to the excavation operation. However, it can be observed that the difference in ground settlements for all anchoring systems at distances larger than 15 m from the shotcrete wall is negligible. Similar to the discussion on the wall deformations, the smallest drilling angle lead to the most favorable outcome with the smallest settlements (Figure 7).

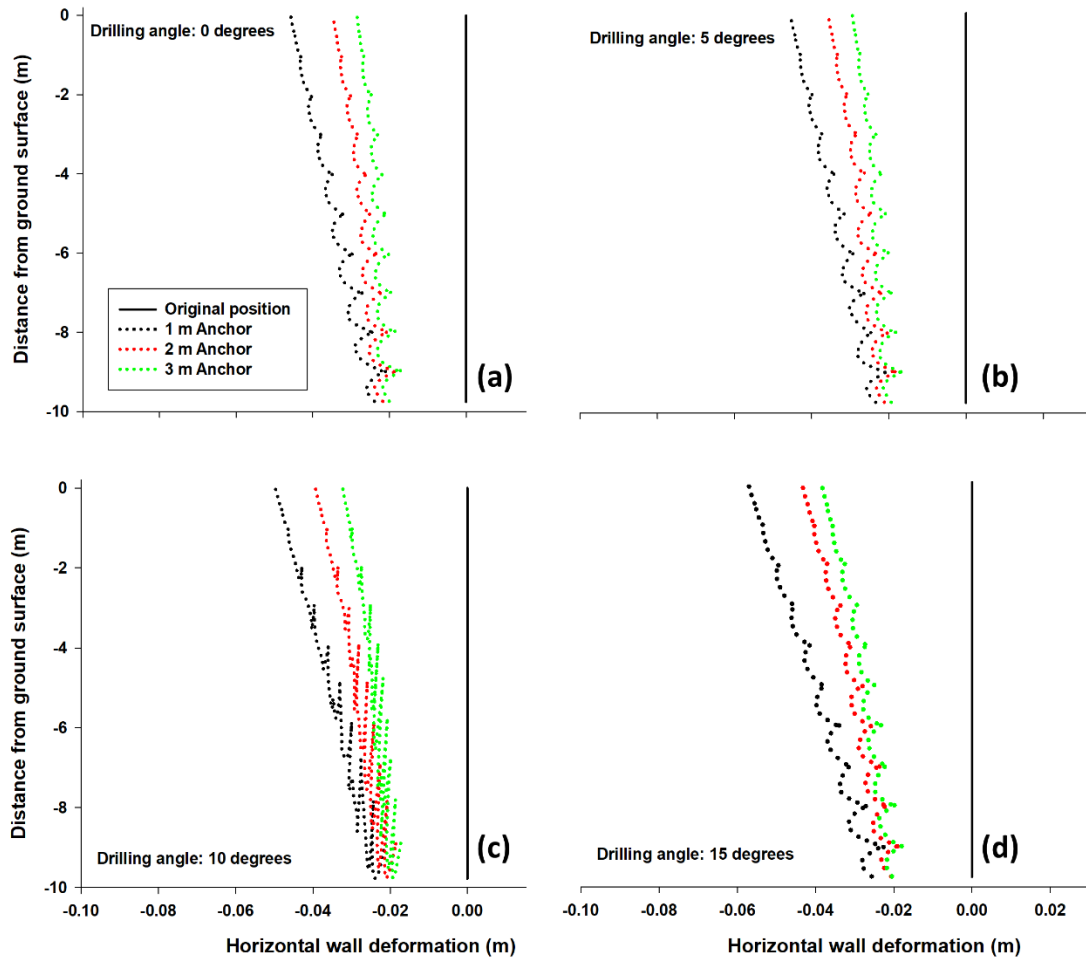


Figure 4. Wall Deformation Graphs for Different Anchor Lengths and Nailing Inclinations of (a) 0 degrees, (b) 5 degrees, (c) 10 degrees, and (d) 15 degrees.

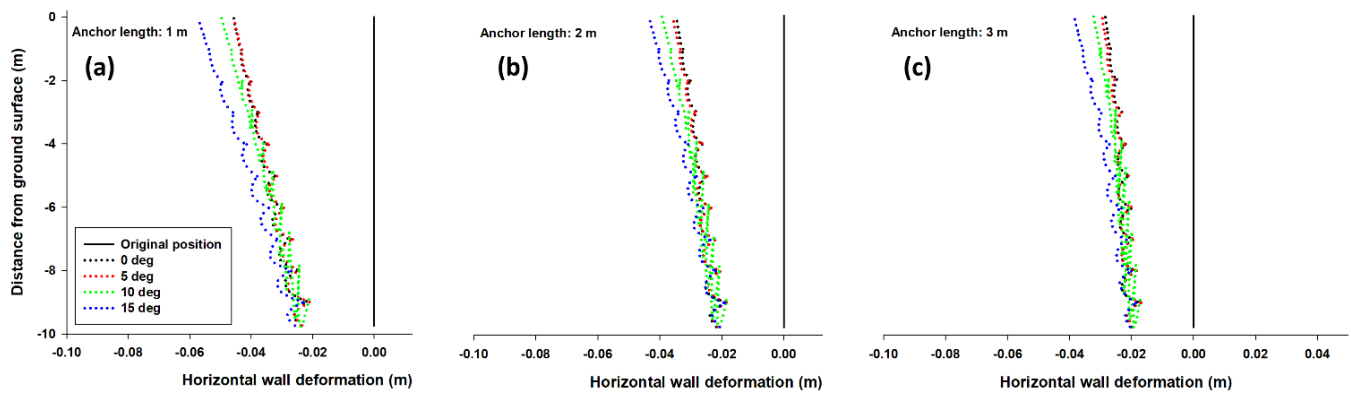


Figure 5. Comparison of The Wall Deformation Profiles for Different Drilling Angles of Cases With (a) 1 m, (b) 2 m, and (c) 3 m Anchor Lengths.

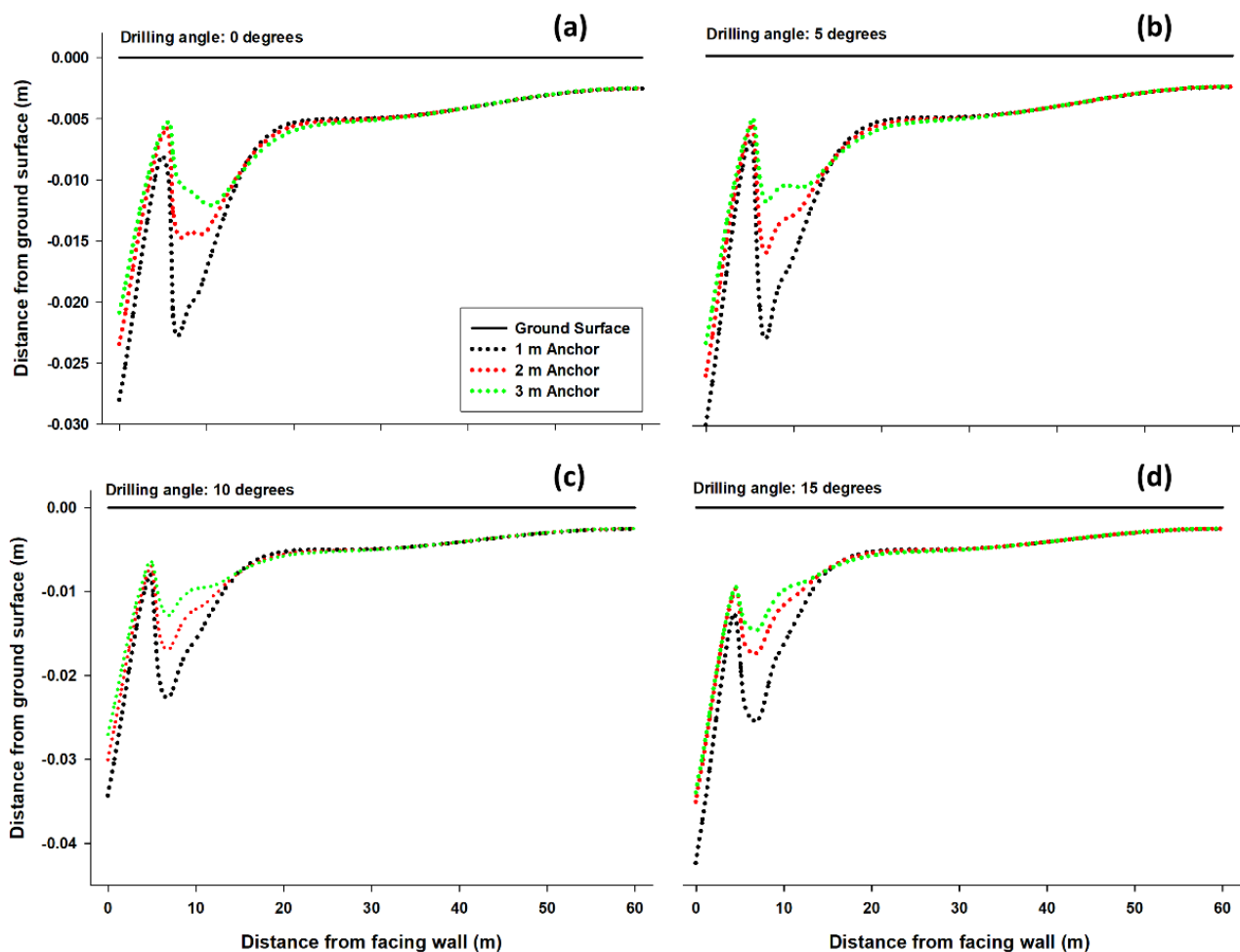


Figure 6. Ground Settlement Graphs for Different Anchor Lengths and Nailing Inclinations of (a) 0 degrees, (b) 5 degrees, (c) 10 degrees, and (d) 15 degrees.

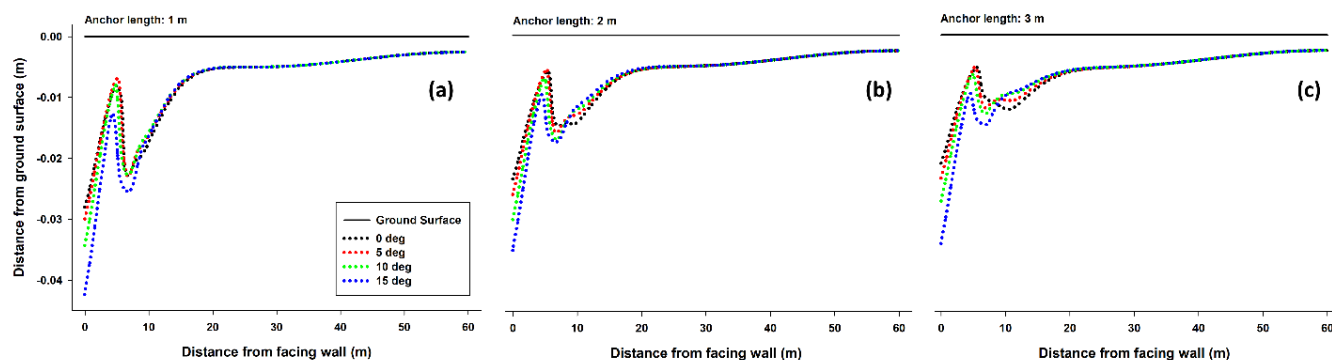


Figure 7. Comparison of The Ground Settlement Profiles for Different Drilling Angles of Cases with (a) 1 m, (b) 2 m, and (c) 3 m Anchor Lengths.

7 Conclusions

The parametric studies concerning geotechnical infrastructure have long been assisting engineers to improve their understanding of the unknown phenomena. While experimental investigations will comprise a substantial portion of research contributing to the field, the occasional costly and unwieldy apparatuses for such evaluations are significant

drawbacks. Consequently, numerical modeling methods can be used as a substitute for the representation and assessment of problems with less financial burden. In the current study, the FHWA (1999) design recommendations for the design of anchored walls were evaluated through a number of parametric studies for an anchored wall. The results were first validated through earlier experimental investigations and were then extended to other scenarios. The observations can eventually be summarized as follows:

- 1) The horizontal displacements of the wall decreased from the wall stem to its toe. While the lateral wall displacements decreased with anchor length, the inclination angle of drilling could adversely affect the nails' performance against lateral loading. Ideally, the best practice is for the nails to be placed at zero angle with the horizontal. However, limitations concerning drilling operations would usually lead to inclined nails with the drilling angles of about 10 degrees.
- 2) Ground settlements improved with the anchor length as less lateral deformation in the walls occurred. This was specifically noticeable in the vicinity of the wall stem. Nevertheless, the induced settlements in all anchor-length scenarios tended to converge to same values with distance from the stem.
- 3) The settlements far from the wall stem were found to follow a similar pattern for different nailing inclinations; same settlement values for all inclination degrees. The ground vertical deformations were also observed to be directly proportional to the drilling angles.
- 4) Although the results of the current study are focused on the deformation patterns of the wall and ground, other graphical presentations for different types of stress, strain, and constitutive relationships could easily be derived from every model built in the software. Additionally, a variety of influential factors such as soil strength parameters and geometrical aspects of the models could be scrutinized for further investigations. These evaluations would significantly reduce the costs associated with physical modeling and can expedite analyses with regard to any modifications in design and planning.

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