Measurement 73 (2015) 341–351

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Parametric assessment of soil-nailing retaining structures in cohesive and cohesionless soils

Soheil Ghareh

Department of Civil Engineering, Payame Noor University, P.O. Box 19395-4697, Tehran, Iran

ARTICLE INFO

Article history:
Received 8 August 2014
Received in revised form 6 November 2014
Accepted 29 May 2015
Available online 6 June 2015

Keywords:
Soil nailing
Excavation
Soil properties
Surcharge
Internal friction angle

ABSTRACT

Soil nailing is an effective stabilizing method for slopes and excavations and has been widely used worldwide. It is a reinforcing method using the shear strength of in-situ ground and the pull-out resistance of soil nailing. Research on numerical schemes of soil-nailing retaining structures has been quite intensive in the past three decades. 'Plaxis' finite-element modelling software is very commonly used for numerical simulations. There are difficulties associated with accurately modelling behaviours of these structures in both cohesive and cohesionless soils. Hence, in the present study, the significant influence of the shear strength of soil-nail cut and of the amount of surcharge on the structural behaviour of soil-nailing retaining walls is discussed. The results show that the soil's physical properties and surcharge directly influence the soil-nailing structures. Another important conclusion is that a soil-nailing structure consisting of nails and tiebacks can be considered a good alternative to improve the safety of excavation walls due to its satisfactory behaviour in the numerical simulations.

1. Introduction

Soil nailing is an in situ construction technique used for enhancing the stability of retaining walls, slopes, and excavations. Because of advantages such as low cost, easy construction, mature construction techniques, and short construction period it has been widely used in engineering. It can be used to allow the safe over-steepening of new or existing soil slopes or as a remedial measure to treat unstable natural soil slopes. The method involves the insertion of reinforcing elements (i.e., nails) into the slope. General-purpose reinforcing bars ('rebar'), but also hollow-system or proprietary solid bars are available. Hollow bars may be drilled and grouted simultaneously by a sacrificial drill bit, pumping grout down the hollow bar as drilling progresses; solid bars are usually installed into pre-drilled holes and then grouted into place using a separate grout line.

Nails work predominantly in tension, under certain circumstances, but may also work in bending and/or shear. Nails are integrated tightly with the soil around them; therefore they can form a type of composite soil. Such composite soils rely mainly on the frictional force of the contact surface. The details of a typical nail and tension anchors are presented in Figs. 1 and 2.

Many observations have been made on the performance of experimental retaining walls reinforced with dynamically driven nails [1–4]. Yin et al. [5] presented a simplified analytical method for calculating the maximum shear stress of the nail-soil interface. In order to examine the effects of several important parameters on the maximum shear stress of the nail-soil interface, they conducted an extensive parametric study. It was observed that when there was no grouting pressure, maximum shear stress increased with decreasing drill-hole radius or increasing

E-mail address: ghareh_soheil@pnu.ac.ir

http://dx.doi.org/10.1016/j.measurement.2015.05.043

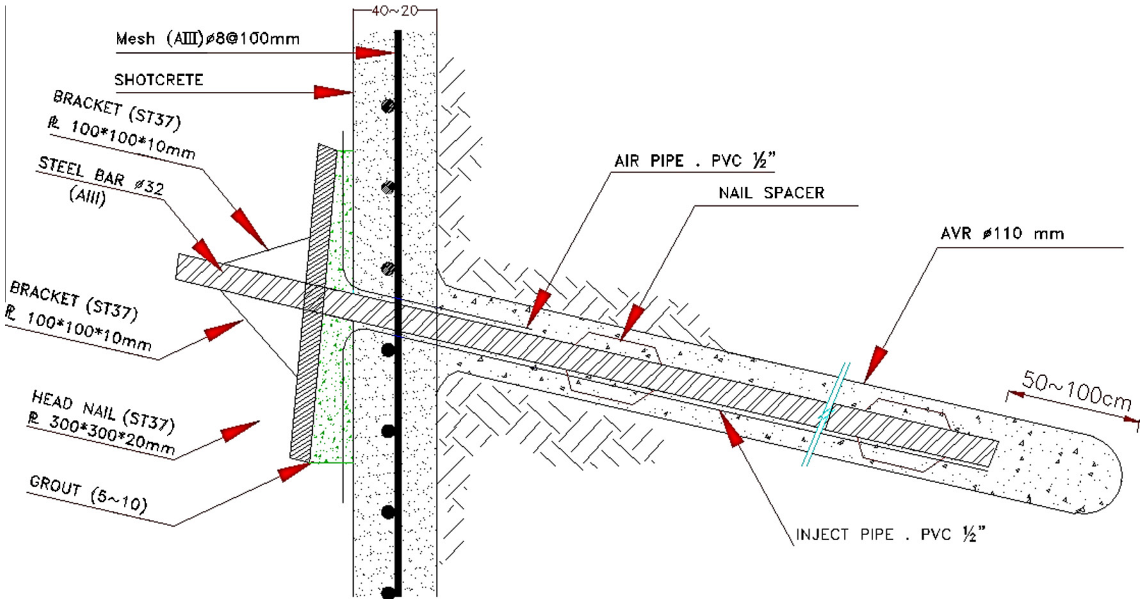

Fig. 1. The details of a typical soil nail system.

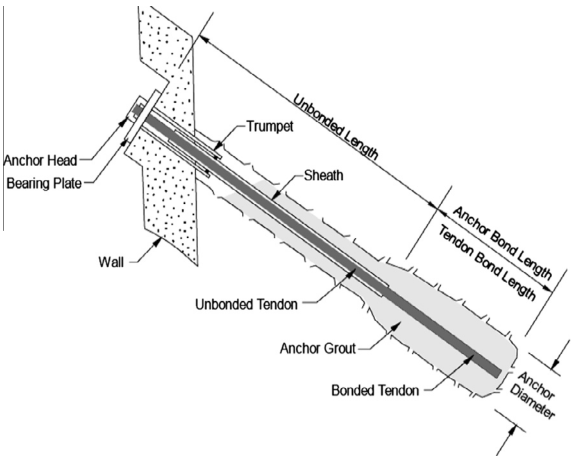

Fig. 2. Details of tension anchors.

failure surface distance, overburden pressure, or dilation angle. Zhang et al. [6] used centrifuge model tests and investigated failure and deformation of a nailing-reinforced slope. They performed a series of centrifuge model tests under vertical-surface loading conditions, considering different nail lengths and slope gradients. The deflection of nails increased with the increasing load pressure, and showed diverse features in distribution in the lower and upper parts of the slope. Ng and Lee [7] also used a three-dimensional parametric to study soil nails for stabilizing tunnel faces. Cheuk et al. [8] investigated on numerical experiments of soil nails in loose fill slopes subjected to rainfall infiltration effects. Davies and Morgan [9] studied on the serviceability of soil nailed slopes. They evaluated the influence of the effective stress on the serviceability of nailed cut slopes. Their experiments showed that the nail loads can increase remarkably when an earth structure is subjected to a reduction in effective stress. Such reduction will normally occurs from an increase in pore water pressure.

Wu et al. [10] studied the influence of cohesion (C) and internal-friction-angle (φ) values on a slope reinforced by a soil-nailing wall in a thick miscellaneous fill site. They concluded that the internal friction angle and cohesion of the soil (i.e. shear strength parameter of the soil) have great influence on the stability of the soil nailing slopes. Their analysis shows that if c and φ values are reasonably chosen, the slope reinforced by soil nailing wall will be much safer. Cheuk et al. [11] investigated the effect of soil-nail orientations on stabilizing mechanisms of loose-fill slopes. They recommended the use of steeply inclined nails throughout the entire slope to prevent global instability, although stating this could lead to significant slope movement, especially with prevailing sliding failure. Dong et al. [12] explored seismic analysis and design methods for soil-nailing retaining walls. Their analysis model provides a new approach for seismic design and seismic analysis of soil-nailing retaining walls.

Zhang et al. [13] discussed extensively the relationship between stability and deformation of soil-nailing structure. They offered a new idea and method to determine deformation of similar supporting structures. The new method has some significance for improving the specifications of foundation pits. They also calculated the deformation of soil-nailing structures. Zhang et al. [14] evaluated the load-deformation behaviour of soil nails using a hyperbolic pull-out model. They studied the interaction mechanism of a soil nail and the surrounding soil and its influential factors. Accordingly, a hyperbolic shear stress–shear strain relationship was proposed using a pull-out model to define the load-deformation behaviour of a cement-grouted soil nail. The proposed model was efficient and accurate, as the laboratory soil-nail pull-out test results in the literature were highly consistent with simulation results.

Wang and Wu [15] proposed a new technique to calculate the seismic active earth pressure of soil-nailing retaining structures. Their results show that lateral pressure of supporting structures under earthquake ground motions can be effectively reduced with soil nails. Seo et al. [16] investigated the optimization of soil-nailing retaining wall design considering three failure modes: shear failure, the pull-out failure, and face failure. They theoretically verified the mechanical behaviour of face failure, shear failure, and pull-out failure. The proposed design procedure of soil nailing presented here could be a more satisfactory design procedure in the actual field.

In the last decades the technology of shorting systems, particularly soil-nailing retaining structure, has significantly improved. Some of the most recent technology is mentioned above. The main objective of the present research is to assess the behaviour of soil-nailing retaining structures after a parametric assessment of the measured data from numerical simulation for a real-scale soil-nailing retaining structure.

2. Materials and methods

The research area was an excavation project, the 'Habib hotel', located in Mashhad, Khorasan Razavi, in Iran. The excavation area was 1050 m^2. The 10-storey building includes a three-storey basement. The required excavation depth was 13 m. Several shorting systems were used in this project including a soil-nailing retaining wall, soil anchorage with steel pile, and rebar mesh covered with shotcrete. Fig. 3 shows the plan of the excavation project and the positions of the steel-column supporting system and the adjacent building next to the excavation area.

The selected excavation support systems considered in this project were designed as temporary. Notably, temporary earth-retaining structures (e.g., soil-nailing retaining structure) allow the sides of the excavation to be cut vertically or near vertically. In this excavation support structure four rows of anchorage systems with length between 12 and 18 m were used. The vertical distance between each row of the tension anchorage was 3 m. The first anchorage row was installed at a depth of 2.5 m from the ground. The excavation was also supported by a series of steel columns at a distance that varied between 3 and 3.5 m.

In order to construct a soil-nailing retaining wall the excavation was performed using the staged-construction method. In the first stages the soil was excavated to a depth of between 1.5 and 2 m. Then the excavated section was covered with a special rebar mesh. Finally, the soil surface reinforced with the rebar was covered with 10-cm-thick concrete using the shotcrete technique. The position of the nails and anchors were highlighted in the wall. Then, using the drill wagon a hole of diameter 10 cm was drilled into the soil. The hole was drilled at an angle of 15°. After installing the required main rebar inside the hole, the hole was filled using an appropriate grout-injection technique (usually water/cement, ratio of 0.4). The east view of the 13-m-heigh soil-nailing retaining structure is shown in Fig. 4.

2.1. Soil properties

The geotechnical properties of the soil are key in designing the soil-nailing retaining structures. The physical properties of the soil are obtained from several boreholes made on the site. The soil layers consist of gravelly clay at both the top and bottom, and clay sand at the middle. In the present study, the Mohr Coulomb (MC) model is used to represent the soil behaviour. The MC model is an elastic, perfectly plastic model, which combines Coulomb's failure criterion and Hooke's law. It is a first-order model for soils, which requires the five basic input parameters, namely Young's modulus (E), and Poisson's ratio (v) for soil elasticity, soil friction angle (φ) and soil cohesion (c) for soil plasticity and the dilatancy angle (ψ). The properties of soil and the interface material used in the numerical simulation are shown in Table 1.

2.2. Soil-nailing materials

In the finite-element modelling, the soil-nailing retaining-structure components are carefully modelled including, the nailing and retaining-wall structure (performed by thin reinforced concrete). In practice, bending stiffness of the soil nails is often considered in the numerical modelling of soil-nail walls [17]. Significantly, few researchers prefer to ignore the contribution of shear and bending capacity of soil nails [18]. Shear and bending resistance of soil nails is conservatively ignored in the conventional analysis and design of soil-nail walls. However, Singh and Babu [19] considered bending stiffness, showed normally with EI, of soil nails in their analysis of soil-nail walls. As stated, the plate structural element in Plaxis can be used to perform analysis of soil-nail walls considering bending stiffness of soil nails (bending stiffness – EI). On the other hand, geogrid structural elements can be used to model the anchors considering axial stiffness of soil nails. In such cases the axial stiffness (EA) is known as the main input parameter.

In this project, for the vertical steel column 2 IPE 200 was selected in order to avoid even small displacement in the excavation walls located next to the buildings. The properties of the used steel pile are presented in Table 2. The strands (tension anchors) included in two sections were bond length and unbond length. All anchors were prepared with four strands. The properties of each strand are shown in Table 3. In addition, a 10-cm-thick shotcrete layer was applied to prevent the soil from weathering and/or surficial failure. Table 4 showed the properties of the shotcrete used in the finite element model.

2.3. Finite element modelling

A numerical study using finite-element analysis software (Plaxis 2D, version 8.5) was carried out. This software enables the user to analyse vast geotechnical problems such as deep excavations, tunnel excavations, and underground structures. In order to set up a model with Plaxis 2D, three fundamental components of a problem must be specified:

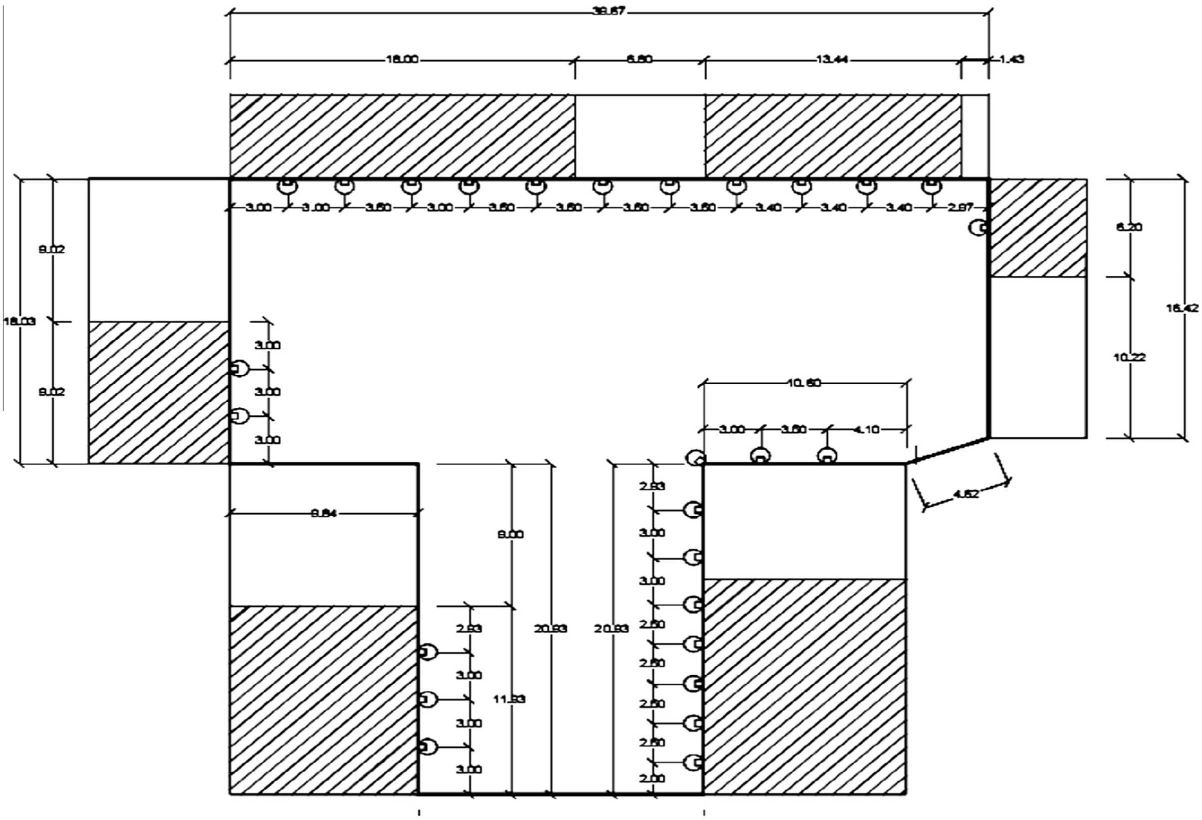

Fig. 3. Plan of excavation and the position of the steel column supporting system.

Fig. 4. A schematic view of the 13 m height soil nailing retaining structure on the east side of the project.

1. Generation of mesh;
2. Constitutive behaviour and material properties;
3. Initial boundary conditions.

The geometry of the problem is discretized into meshes or grids, as shown in Fig. 5. The associated material properties and constitutive behaviour dictate the type of response the model will display upon disturbance (loading). Initial and boundary conditions define the state of the model being simulated. Since finite element techniques are the most rigorous methods, we chose such a technique to investigate the stability of soil-nailing retaining structures. In this article, the elasto-plastic material type (MC) was used for the analysis of the nailed soil cut.

The retaining structures were modelled in Plaxis as a plane-strain condition in a 2D environment. The excavation is modelled in various stages. The soil is modelled with 15-node triangular finite elements. In the area of the soil-nailing retaining structure, because stresses and displacements are higher in this area the considered medium mesh size was refined. In Plaxis, to simulate the interaction between structure and soil we can apply interface elements. Without an interface the soil and the structure are tied together: no relative displacement (gapping/slipping) is possible between structure and soil. The material properties of the interface are entered in the same data sets as the soil properties, and related to the soil properties. For interaction between soil-nailing structure and available

Table 1
Soil and interface material information.

Name	Type	γ_{sat} (kN/m^3)	ν (–)	E (kN/m^2)	c (kN/m^2)	φ (°)	R_{inter} (–)	SPT N_{SPT}
Gravelly clay	Drained	19	0.25	9000	20	29	1	25
Clayey sand	Drained	20	0.25	12,000	5	32	1	35

Table 2
Properties of the used steel pile.

Profile name	Length (m)	E (kPa)	ν	Area (cm^2)	I (cm^4)
2 IPE 200	15	2.05×10^{11}	0.2	570	38,800

Table 4
Properties of the shotcrete modelled in Plaxis.

Height (m)	Thickness (cm)	Width (m)	E (pa)	Poison ratio
13	10	3	2.7×10^{10}	0.2

soil, the soil layer is stronger than the interface, which means that interface strength (R_{inter}) should be less than 1.

In most geotechnical application works, a definite reduction is assumed for the strength properties at the interface between the soil and structures to consider the disturbance of the shield excavation. For example, the suitable values for R_{inter} for the case of the interaction between various types of soil and structures in the soil can be found in the literature. Based on the Plaxis manual, the interface [sandy cobble ($R_{inter} < 1$)] reduces by 33% the interface friction and cohesion, compared to the normal sandy cobble soils. In this study the magnitude of R_{int} was taken 1.0 which means the interface is considered as rigid.

The modelling process was performed in four steps, namely soil, shotcrete, anchor (bond and unbond length), and applied surcharge. A refined medium mesh consisting of around 1119 elements was adopted. The bottom and lateral boundaries were placed at locations at appropriate distance. Table 5 shows the brief outline of various models of materials along with a number of stress points and elements for each model. Fig. 5 shows the schematic view of the FEM deformed mesh obtained in the Plaxis model simulation of the behaviour of the retaining structure during excavation.

3. Results and discussion

The stability and structural behaviours of the nailing retaining wall mainly relies on several physical properties of the soil. The properties discussed in this research paper are cohesion, internal friction angle, and modulus of elasticity. The effects of surcharge next to the excavation site on the behaviours of soil-nailing retaining structures were assessed. For the mentioned design parameters the wall displacement, axial force, shear force, and bending moment along the excavation (per metre) were obtained from the excavation vertical facing. The results varied versus depth for the nailed cut wall.

Table 3
Properties of the used strands.

Tension anchor	Length (m)	E (pa)	Area of each strand (mm^2)
Bond	8	2.1×10^{11}	140
Unbond	Varied	2.05×10^{11}	140

3.1. Effect of surcharge

The results for the effect of surcharge on the horizontal displacement, axial force, shear force, and bending moment of the soil-nailing retaining wall, which varied versus depth, are presented in Figs. 6–9, respectively. As stated above, such variation also depends on the soil's physical characteristics. Fig. 6 indicates that for the soil-nail cut used in this research the wall displacement increased with the depth of the wall. The wall displacement was increased along the wall surface almost linearly up to a particular depth.

For the surcharge pressure of 20 kPa, the horizontal displacement varied between 3 mm and 8 mm for depths of 0–10 m, respectively. However, in a same depth, horizontal displacement for the 60 kPa surcharge varied between 6.3 mm and 12.8 mm. The most horizontal displacement occurred at a depth of between 9 and 11 m, corresponding to 70–85% of the wall's height. After this depth the displacement significantly decreased (up to 36%) to the wall's base.

Fig. 7 shows the results of axial force along the shotcrete wall. It can be seen that increases in the surcharge from 20 kPa to 60 kPa lead to an increase in the axial force of the retaining wall. The weight of the soil-nailing retaining structure is neglected in the calculation as it may help the stability of the system. The results show that axial force suddenly increased at depths of 2.5 m, 5.5 m, 8.5 m, and 11.5 m. At these points nails were installed. The larger the surcharge, the larger the axial force was measured in the nailing retaining wall. It is important to note not only the larger axial force obtained at the nailing point but also the larger increases measured when larger surcharge loads were applied. This is due to the more normal stresses transferred from the nails to the vertical shotcrete retaining walls. The efficiency of the nails is also dependent on such load-transforming conditions. The axial measured load from the simulated anchors indicates the amount of reaction that the nail takes from the soil-nail cut.

The results for shear force and bending moment along the shotcrete wall are presented in Figs. 8 and 9, respectively. The effects of surcharge loading on both the shear

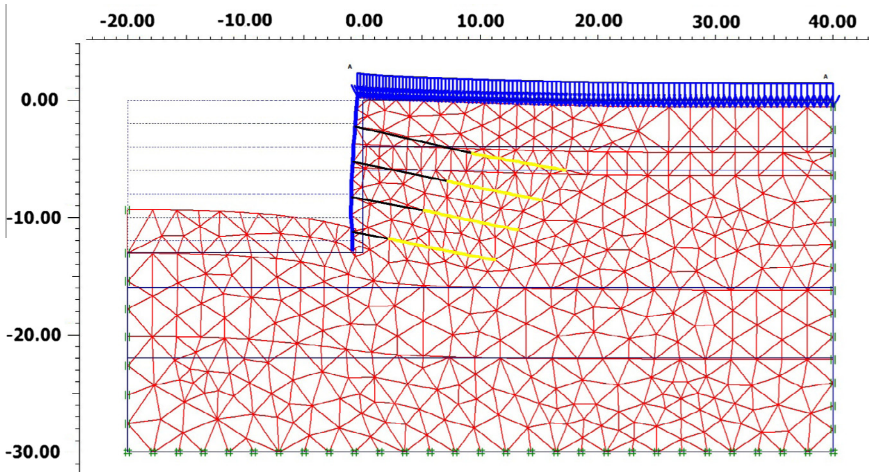

Fig. 5. FEM deformed mesh obtained in Plaxis simulation of the behavior of the retaining structure during excavation.

Table 5
The brief outline of various models of materials in the simulated model.

Parameter	Description
Model	Plane strain
Element	15-Noded
Number of elements	1119
Number of nodes	9147
Number of stress points	13,428
Average element size	1.27 m

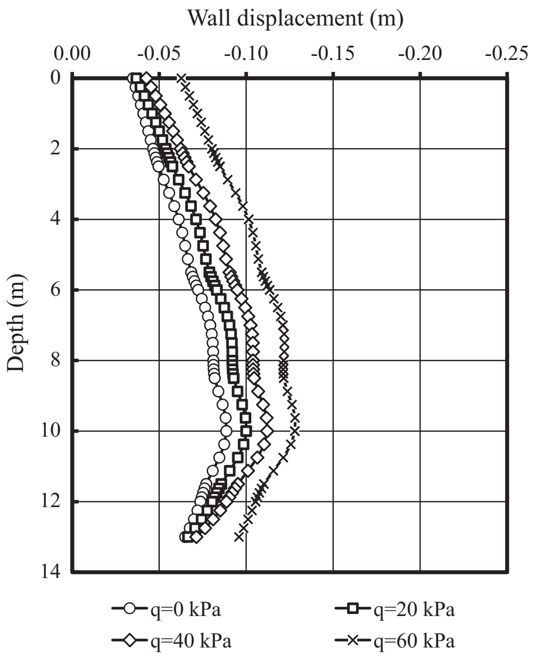

Fig. 6. Effect of surcharge on the variation of wall horizontal displacement versus depth.

force and bending moment of the soil-nailing retaining structure can be seen. The greater the surcharge loads applied to the soil-nail cut, the higher the shear force and bending moments measured for the vertical shotcrete nailing walls corresponding to the greater strength required for the stability of the designed retaining wall. The effect of nails can be clearly seen by breaking the shear force from a positive value (on the left side of the diagram) down to negative values (on the right side of the diagram). Similarly, the presence of nailing caused a remarkable decrease in the bending moment in the reinforced shotcrete wall. Indeed, where the wall showed the highest horizontal displacement, the highest bending moment and the highest changes in the shear force from positive to negative were obtained. The increases in surcharge from

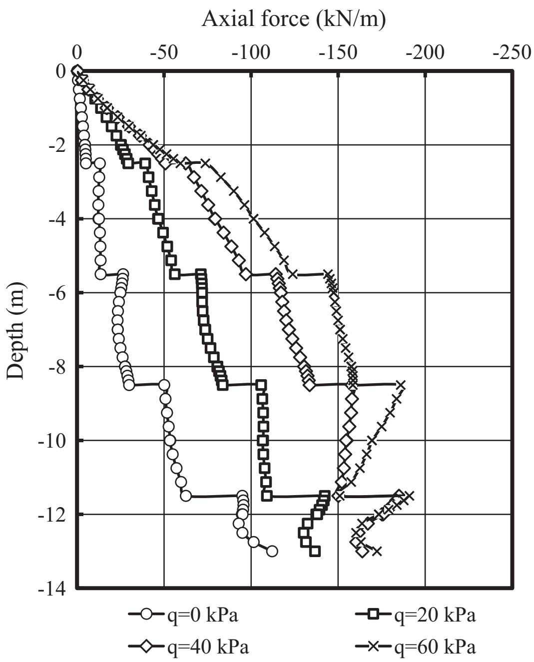

Fig. 7. Effect of surcharge on the variation of axial force along the soil nailing retaining wall.

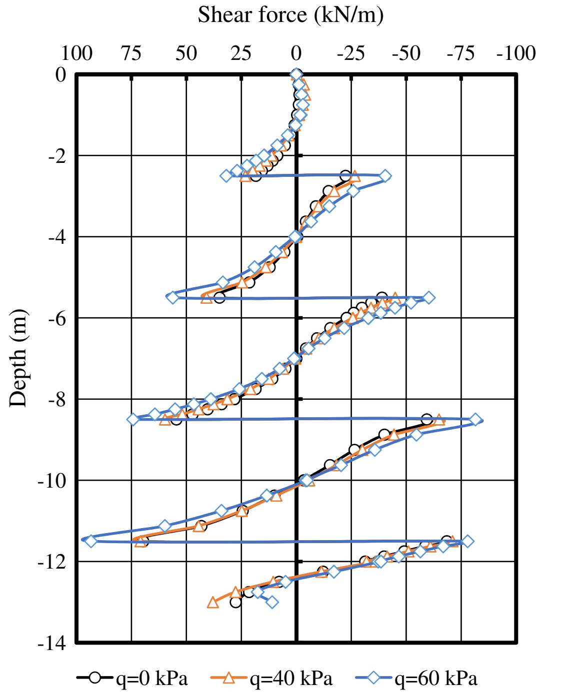

Fig. 8. Effect of surcharge on the variation of shear force along the soil nailing retaining wall.

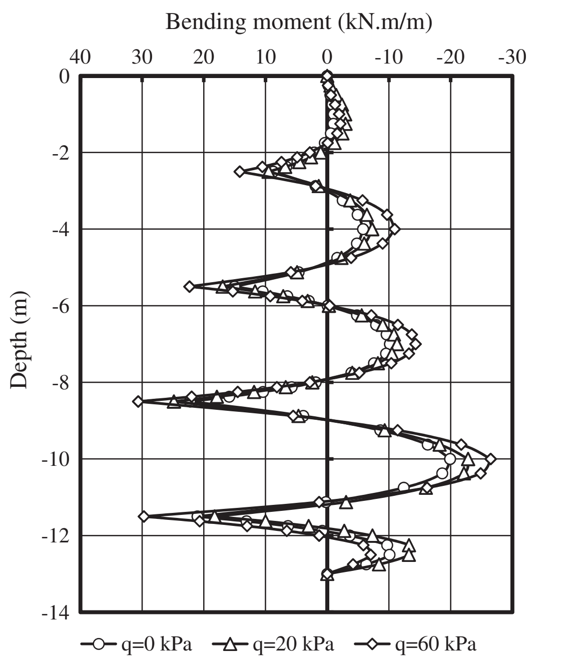

Fig. 9. Effect of surcharge on the variation of bending moment along the soil nailing retaining wall.

20 kPa to 60 kPa at a depth equal to 10 m caused an increase in the bending moment from 18.2 kN m/m to 26.4 kN m/m, respectively. This corresponds to about a 40% increase in bending moment after tripling the surcharge load (Fig. 9).

3.2. Effect of soil cohesion

Cohesion is the force that holds molecules or like particles within a soil together. In this project the values of soil cohesion are obtained from both SPT results and direct shear test results. Bowles [20] stated that for the cohesive soil with an SPT value between 16 and 32, the soil can be considered very stiff. In this section we explored the effect of soil cohesion on soil-nailing retaining-wall behaviour. Figs. 11–14 show the significance of the soil cohesion on the horizontal displacement, axial force, shear force, and bending moment of the soil-nailing retaining wall, respectively.

In order to assess the effect of cohesion, four different cohesion values were used of 1 kPa, 10 kPa, 20 kPa, and 30 kPa. In reality, the cohesion of the soil cannot be zero; therefore, the minimum selected cohesion in the simulated model was 1 kPa. The obtained results show a significant effect of the soil cohesion property. When the cohesion is ignored (i.e., in the cohesionless soil) the horizontal displacement of the wall is much larger than with soil with a cohesion of 10 kPa. In this research the soil-nail cut with cohesion of 1 kPa and 10 kPa resulted in wall displacement of 0.21 m and 0.074 m, respectively. This shows even a small amount of cohesion can significantly affect the wall displacement rate. Unlike the cohesive soil, where the highest displacement rate was found in the depths near to the wall's base, in cohesionless soil (i.e., gravelly and sandy soils) the highest displacement occurred at the base of the wall (Fig. 10).

Fig. 11 shows the results of axial force along with the depth for the studied soil nailed cut with four different cohesions. The effect of soil cohesion on the wall's axial force mainly depends on the applied normal stress (i.e.,

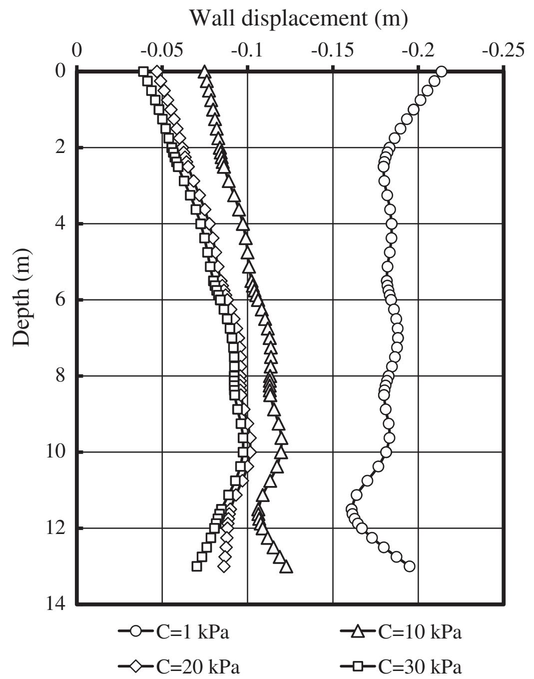

Fig. 10. Effect of cohession on the variation of wall horizontal displacement versus depth.

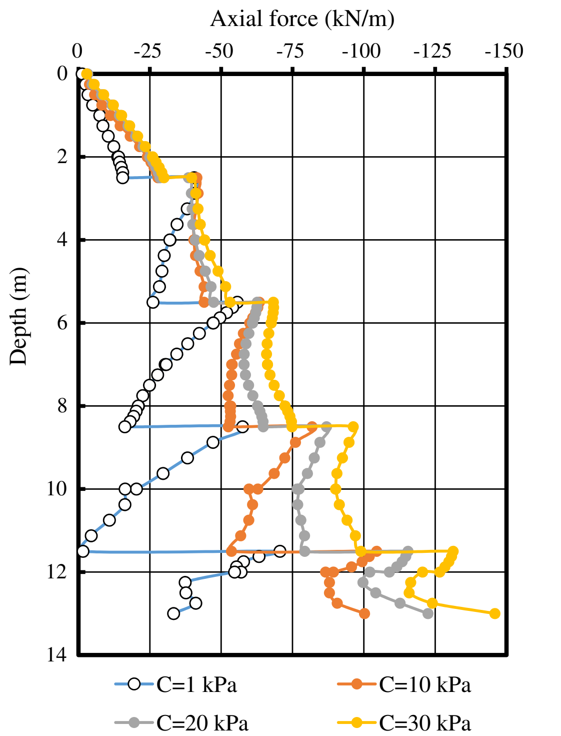

Fig. 11. Effect of cohession on the variation of wall axial force versus depth.

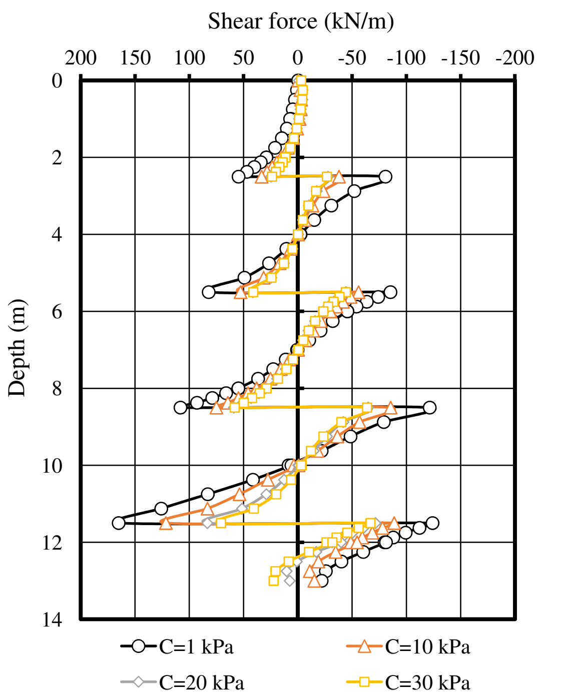

Fig. 12. Effect of cohession on the variation of wall shear force versus depth.

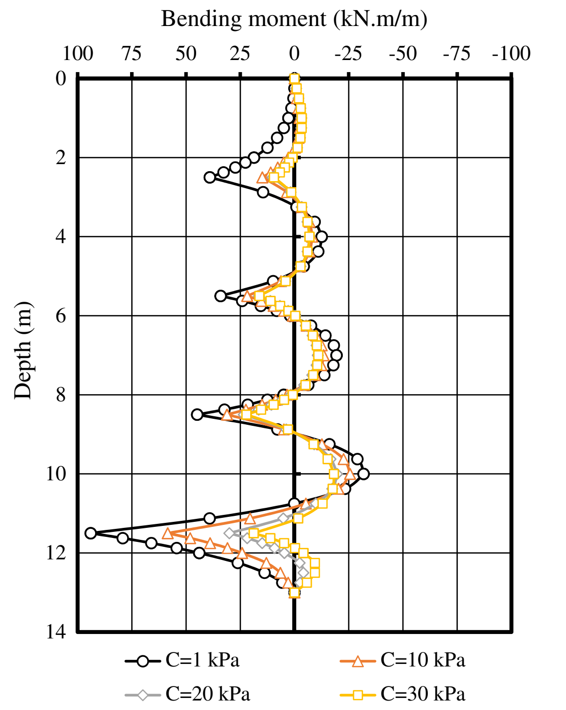

Fig. 13. Effect of cohession on the variation of bending moment versus depth.

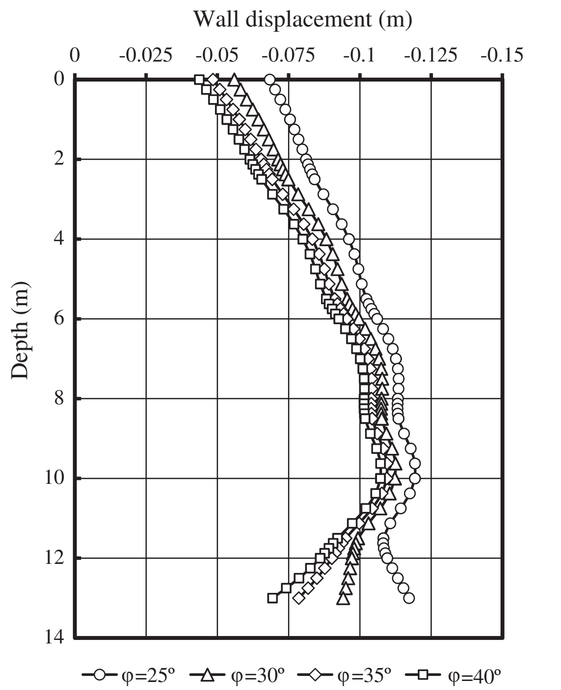

Fig. 14. Effect of internal friction angle (φ) on the variation of wall horizontal displacement versus depth.

increases with depth) and the properties of the nail and facing. It can be seen that in the soil-nailing retaining structure, the higher the soil cohesion the larger the measured axial force along the shotcrete facing. For instance, at a depth equal to 10 m from the ground, the axial forces for the cohesions of 1 kPa, 10 kPa, 20 kPa, and 30 kPa were −20.3, −62.82, −77.3, and −90.1 kN, respectively. In addition, the reaction in the nailing point is largely affected by the cohesion. The efficiency of the nails in transferring the loads to the wall (i.e., as a vertical axial force) can be calculated by considering the differences in the axial force in the nailing levels (Fig. 11). This is also increased by increasing the normal stress (i.e., increasing the depth of the excavation). The obtained result proves that when there is cohesionless soil in the field the shotcrete wall must be designed for the larger axial force. This is also shown in Figs. 12 and 13 for the shear force and bending moment obtained from the soil-nailing retaining wall, respectively. For soils with greater cohesive strength a lower measured shear force in the reinforced shotcrete wall resulted. At a depth of 11.5 m from the ground, for the last nails installed from above the shear force varied from 70 kN to −66 kN when the cohesion was 30 kPa. However, the shear-force variation for cohesionless soil was between 165 kN and −124 kN. The larger difference indicates a stronger retaining wall is required (Fig. 12). The bending moments are obtained at the maximum values where the shear force is zero (i.e., at depths equal to 4 m, 7 m, and 10 m). Significantly, the bending moment at the lower parts of the wall is much larger when we eliminate the soil cohesion. For example, the measured bending moments applied on the shotcrete wall were 18.8 kN m/m and 94 kN m/m for soil with cohesion equal to 30 kPa and 1 kPa, respectively. Such differences are much smaller at shallow depths, which proves the importance of normal stresses on the bending moment.

3.3. Effect of soil internal friction angle

It is also very important in designing soil-nailing retaining structures to consider the internal friction angle (φ) of the adjacent soil. This is because the earth pressure distributes mainly according to the internal friction angle of the soil. For instance, the term K, which indicates the lateral earth pressure coefficient of the soil, can be calculated from $K = 1 - \sin\varphi$ (i.e., for at-rest earth pressures). A larger φ results in lower K, which reduces the amount of pressure exerted by the soil on the retaining walls. Unlike the significant effect of cohesion on wall deflection, the changes in the internal friction angle (i.e., from 25° to 40°) show little effect on the displacement of the wall. Soil with $\varphi = 25°$ shows a larger displacement ratio than soil with $\varphi = 40°$. This is due to lower soil pressure applied on the shotcrete wall facing. The maximum wall deflection is observed at a depth equal to 10 m (or 77% of the wall's height from the ground) for φ equal to 25, 30, 35, and 40, equal to 11.9 cm, 11.2 cm, 10.9 cm, and 10.7 cm, respectively (Fig. 14). The wall's drift (non-uniform deflection between the top of the wall and the maximum-displacement point) is observed to be almost 6 cm for all cases. In some excavations such drift should be controlled; this may require a stronger shotcrete wall design. Accordingly higher bending stiffness can significantly reduce the wall's horizontal displacement.

The effects of internal friction angle (φ) on the variation of the wall's axial force, shear force, and bending moment versus depth are presented in Figs. 15–17, respectively. Soil with a higher internal friction angle leads to higher axial force being transferred to the shotcrete retaining walls. The measured axial force at 10 m depth from the ground for φ equal to 25, 30, 35, and 40 was −54.4 kN, −75.4 kN, −92.5 kN, and −105.6 kN, respectively. As stated above, the axial loads were increased in nailing locations, such as z, equal to 2.5 m, 5.5 m, 8.5 m, and 11.5 m from the ground. It is interesting to note that in low-friction-angle soils the amount of axial force transferred by the nails is larger compared with soil with higher internal friction angle. Comparing the obtained results for $\varphi = 25°$ and $\varphi = 40°$ at the depth $z = 11.5$ m can clearly prove this statement (Fig. 15).

In contrast to the axial force (Fig. 15), the obtained shear force (Fig. 16) and bending moment (Fig. 17) along the shotcreted wall showed almost no effect related to internal friction angle. As before, the highest shear force was obtained at $z = 11.5$ m in the last installed nail near the wall's base. Significantly, the soil-nail cut with $\varphi = 25°$ and $\varphi = 40°$ presented the highest and lowest shear force in the retaining walls. This shows that when we consider the nailing system as a possible option for the shorting system, particularly in soils with low friction angles, the shear force is probably the dominant term to be considered in designing the shotcrete retaining

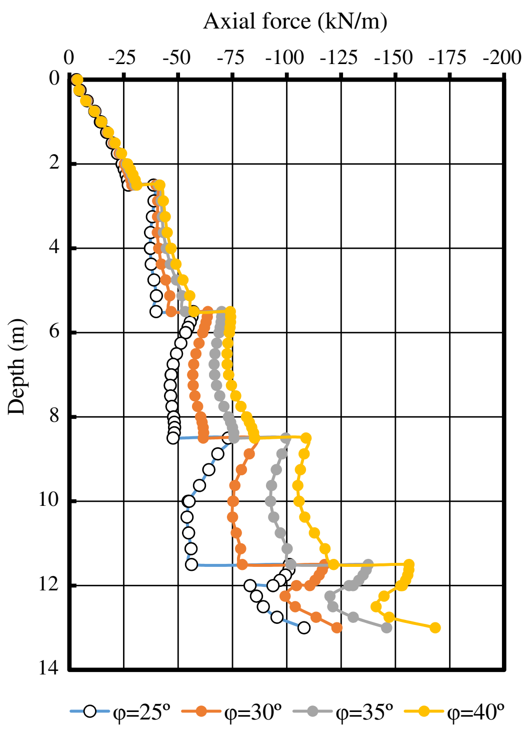

Fig. 15. Effect of internal friction angle (φ) on the variation of wall axial force versus depth.

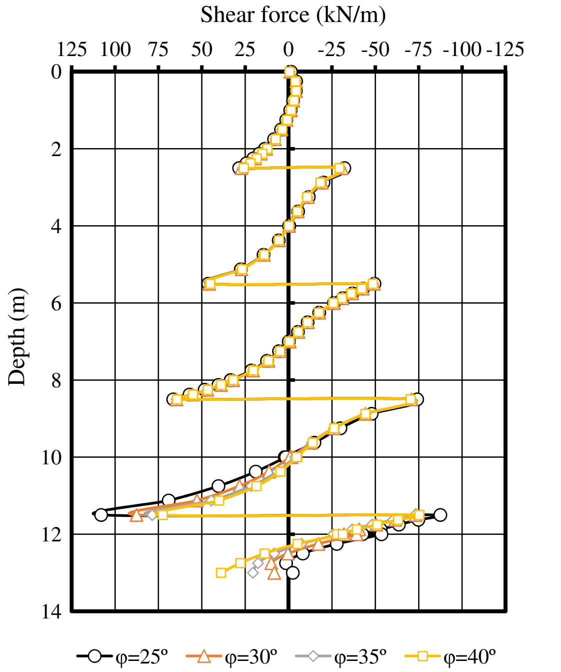

Fig. 16. Effect of internal friction angle (φ) on the variation of wall shear force versus depth.

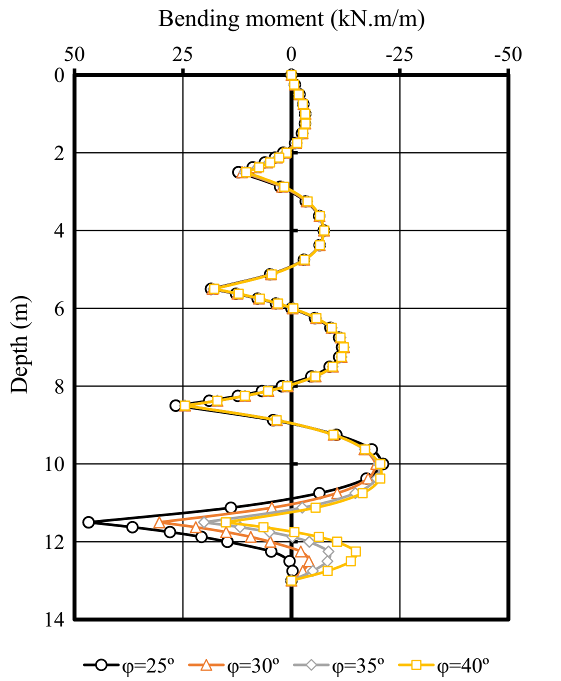

Fig. 17. Effect of internal friction angle (φ) on the variation of bending moment versus depth.

structures (Fig. 16). Similar behaviour was observed in the measured bending moment throughout the wall. Except for $z > 10$ m, there was almost no difference between the bending moment of the soil-nail cut with φ between 25° and 40°. The difference in the wall's base could be due to the joint selected at the base of the wall in the simulated model. Importantly, in the soil-nailing retaining structures, the shotcrete construction continued only up to the excavation level (Fig. 17). In cases where the nailing was supported with a secondary piling system penetrating to a particular depth below the excavation level, the bending moment may not be zero.

By comparing the effect of all considered parameters such as surcharge, soil cohesion, and soil internal friction angle on the axial force, shear force, and bending moment on the shotcreted wall, it can be seen that the higher surcharge has negative effect on the wall stability (i.e. causes higher wall displacement, higher shear and axial forces, and higher bending moment). In reverse, as the shear strength parameters increased the shear and axial forces, bending moment and the horizontal displacement through the shotcreted wall decreased.

4. Conclusions

The main purpose of this research was to determine the importance of shear strength of soil-nail cut as well as the amount of surcharge on the structural behaviour of soil-nailing retaining walls. A numerical study using finite-element analysis (Plaxis 2D, version 8.5) was carried out. The analysis shows that if key parameter values are reasonably chosen, the soil-nailing retaining wall will be much safer, and the project will surely be less wasteful. Based on the various numerical simulations that have been performed the following main conclusions are drawn.

1. The soil's physical characteristics, such as cohesion and internal friction angle, are key for designing a suitable soil-nailing retaining structure. It is observed that even a small amount of cohesion, here 10 kPa was used, can greatly reduce the wall displacement rate. In cohesionless soil the highest displacement of wall occurred in base of the wall; however, in cohesive soil the highest displacement rate happened at depths near the wall's base.
2. Soil with higher internal friction angle leads to higher axial force being transferred to the shotcrete retaining walls. In addition, at low friction angles, the shear force is probably the dominant term to be considered in designing shotcrete retaining structures.
3. The larger the surcharge, the larger was the measured axial force in the nailing retaining wall. This is due to more normal stresses being transferred from the nails to the vertical shotcrete retaining walls. The more surcharge loads applied to the soil-nail cut, the higher the shear force and bending moments measured at the vertical shotcrete nailing walls.

References

[1] G. Cartier, J.P. Gigan, Experiments and observations on soil nailing structures, in: Proceedings of the European Conference on Soil Mechanics and Foundation Engineering, 1983, pp. 473–476.
[2] C.Y. Hong, J.H. Yin, H.F. Pei, W.H. Zhou, Experimental study on the pullout resistance of pressure-grouted soil nails in the field, Can. Geotech. J. 50 (2013) 693–704.

[3] Z. Liu, C. Ma, Z. Zhao, Laboratory experimental study on pullout behavior of mortar grouted GFRP soil nails, Adv. Mater. Res. (2011) 1069–1072.
[4] M.C.R. Davies, C.D. Jacobs, R.J. Bridle, An experimental investigation of soil nailing, retaining structures, in: Proc. Conference, Cambridge, vol. 9, 1993, pp. 587–598.
[5] J.H. Yin, C.Y. Hong, W.H. Zhou, Simplified analytical method for calculating the maximum shear stress of nail-soil interface, Int. J. Geomech. 12 (2012) 309–317.
[6] G. Zhang, J. Cao, L. Wang, Centrifuge model tests of deformation and failure of nailing-reinforced slope under vertical surface loading conditions, Soils Found. 53 (2013) 117–129.
[7] C.W.W. Ng, G.T.K. Lee, A three-dimensional parametric study of the use of soil nails for stabilising tunnel faces, Comput. Geotech. 29 (2002) 673–697.
[8] C.Y. Cheuk, C.W.W. Ng, H.W. Sun, Numerical experiments of soil nails in loose fill slopes subjected to rainfall infiltration effects, Comput. Geotech. 32 (2005) 290–303.
[9] M.C.R. Davies, N. Morgan, The influence of the variation of effective stress on the serviceability of soil nailed slopes, in: Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering: Geotechnology in Harmony with the Global Environment, 2005, pp. 1335–1338.
[10] D. Wu, P. Wang, G.Q. Liu, Influence of C and φ values on slope supporting by soil nailing wall in thick miscellaneous fill site, Adv. Mater. Res. (2013) 504–507.
[11] C.Y. Cheuk, K.K.S. Ho, A.Y.T. Lam, Influence of soil nail orientations on stabilizing mechanisms of loose fill slopes, Can. Geotech. J. 50 (2013) 1236–1249.
[12] J.H. Dong, W. Ma, Y.P. Zhu, Seismic analysis and design method for soil nailing retaining wall, Zhongguo Gonglu Xuebao/China J. Highway Transport 26 (2013) 34–41.
[13] Y.C. Zhang, G.H. Yang, S.J. Wu, L.N. Yao, Z.H. Zhong, Discussion on relationship between deformation and stability of soil nailing structure, Yantu Lixue/Rock Soil Mech. 35 (2014) 238–247.
[14] C.C. Zhang, Q. Xu, H.H. Zhu, B. Shi, J.H. Yin, Evaluations of load-deformation behavior of soil nail using hyperbolic pullout model, Geomech. Eng. 6 (2014) 277–292.
[15] Y.S. Wang, L.H. Wu, The engineering application of new method for calculating seismic active earth pressure of soil-nailing retaining structures, Adv. Mater. Res. (2014) 86–89.
[16] H.J. Seo, I.M. Lee, S.W. Lee, Optimization of soil nailing design considering three failure modes, KSCE J. Civ. Eng. 18 (2014) 488–496.
[17] C.-C. Fan, J.-H. Luo, Numerical study on the optimum layout of soil-nailed slopes, Comput. Geotech. 35 (2008) 585–599.
[18] S. Liew, C. Khoo, Design and construction of soil nail strengthening work over uncontrolled fill for a 14.5 m deep excavation, in: 10th International Conference on Piling and Deep Foundations, 2006.
[19] V.P. Singh, G.S. Babu, 2D numerical simulations of soil nail walls, Geotech. Geol. Eng. 28 (2010) 299–309.
[20] J.E. Bowles, Foundation Analysis and Design, McGraw-Hill, Illinois, USA, 1996.