Geomechanics and Engineering, *Vol. 6, No. 4 (2014) 391-401*
DOI: http://dx.doi.org/10.12989/gae.2014.6.4.391

Numerical modeling of soil nail walls considering Mohr Coulomb, hardening soil and hardening soil with small-strain stiffness effect models

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(*Received December 23, 2013, Revised January 01, 2014, Accepted January 19, 2014*)

Abstract. In an attempt to make a numerical modeling of the nailed walls with a view to assess the stability has been used. A convenient modeling which can provide answers to nearly situ conditions is of particular significance and can significantly reduce operating costs and avoid the risks arising from inefficient design. In the present study, a nailing system with a excavation depth of 8 meters has been modeled and observed by using the three constitutive behavioral methods; Mohr Coulomb (MC), hardening soil (HS) and hardening soil model with Small-Strain stiffness ensued from small strains (HSS). There is a little difference between factor of safety and the forces predicted by the three models. As extremely small lateral deformations exert effect on stability and the overall deformation of a system, the application of advanced soil model is essential. Likewise, behavioral models such as HS and HSS realize lower amounts of the heave of excavation bed and lateral deformation than MC model.

Keywords: soil nail walls; MC model; HS model; HSS model; PLAXIS 2D

1. Introduction

Nowadays, with an increase in urban development and growing development of high-rise constructions, there is a pressing need for the excavations with greater depth. An important issue that we should bear in mind is to provide the stability of the ongoing excavation with an attempt to avoid any forms of potential risks in urban environments. Normally the designs of the nailed walls are created by using FHWA regulations and based on limit equilibrium method. These kinds of retaining structures are endowed with intricate behaviors as this complexity may vary and influence how nailing system behave based on numerous factors such as the interaction of soil and nail operation stages etc. In practice, in order to study the interaction between soil and structure and the assessment of the behavior of the system, wall-soil, a numerical modeling is used in conjunction with various software programs and numerical methods such as finite elements (Smith and Su 1997, Zhang *et al*. 1999, Fan and Luo 2008, Park *et al*. 2013, Seo *et al*. 2012, Yin and Su 2009, Hong *et al*. 2012, Singh and Sivakumar Babu 2010, Nam *et al*. 2006), discrete elements (Kim *et al*. 1997), finite difference (Sivakumar Babu *et al*. 2002). According to previous investi-

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http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

gations, it became evident that the accuracy of numerical modeling is contingent largely upon the behavioral modeling used by Brinkgrou *et al*. (2006) and selecting appropriate values for the parameters used in the model of Calvello and Finno (2004). In order to make numerical modeling of the soil-nail system, the first-rank behavioral model of Mohr-Coulomb is used (Kim *et al*. 1997, Zhang *et al*. 1999, SivaKumar Babu *et al*. 2002, Fan and Lou 2008).

Zhu *et al*. (2012) considered a slope monitoring system based on fibre Bragg grating (FBG) sensing technology. They also discussed the advantages of the slope monitoring system and experience gained in the field implementation.

Komak Panah and Majidian (2013) simulated the dynamic behavior and failure pattern of nailed structures using two series of numerical analyses, namely dynamic time history and pseudo-static.

In order to model nailing systems, we rarely used behavioral systems such as Duncan-Chang hyperbolic model, Briad and Lim's 1997 (SP-model the modified model of Moher-Coloumb by taking into consideration the behavior of being strained (Cheuk *et al*. 2005), Drucker Prager yield criterion (Ng and Lee 2002), and hardening soil model (Liew and Khou 2006). Brinkgrou *et al*. (2006) demonstrated that the high stiffness of the soil at very small strains (i.e., (< 〖10〗 ^(-5)), make a major contribution to the behavior of excavation, foundation and projects with so-called engineering strains, (〖10〗 ^(-3)<).

Benz (2007) developed a model of hardening soil with a stiffness coming from small strains in order to account for the same issue. In general, as the study performed in this research showed, the application of robust behavioral models for numerical modeling predicts more convenient behaviors for nailing systems while requiring the use of computers with high capacity. Moreover, such application calls for intricate geotechnical operations and further engineering judgment based on experience so as to determine model parameters. In the present study, the both models, hardening soil (HS) and hardening soil with hardening effect of small strains (HSS), were used along with Moher-coloumb model (MC) in order to model a nailed wall and theirs results were compared.

2. Methodology and material parameters

In order to achieve the objective defined in the previous section, a ditch with a height of 8 meters, vertical walls was used as horizontal levels was taken for backfill soil.

Furthermore, in this study, the material behind the wall was considered to be homogenous. Wall design was produced based on allowable strains method and using FHWA regulations. The characteristics of necessary structures are presented in table 1 in order to numerically model the soil-nail system. The finite element software, Plaxis 8.5, was taken as numerical modeling and plane strain conditions were applied in the analysis. The three behavioral models, MC, HS and HSS, were used for modeling the wall as their results were compared with each other based after each step of excavation on maximum horizontal displacement as well as axial forces generated in the nails. In what follows, a brief description of the behavioral models, MC, HS and HSS, as well as major parameters used hereto will be offered. The soil used in this study was supposed to be moss of the kind with negligible adhesion. The parameters used for this purpose were chosen based the works of Feng *et al*. (2009) and other similar works and their values as well as descriptions are presented in Table 2. It must be noted that $E_{ur}^{ref} = 3E_{50}^{ref}$ was determined based on Schanz *et al*. (1999).

Table 1 The geometrical characteristics and other parameters of the nailed walls

Parameters	Value
Vertical wall height H(m)	8
Wall slope α	0
inclination angle of the slope β	0
Nailing system type	Grouted
Nails and shotcrete model	Elastic
Rebar yield stress f_y (Mpa)	400
Rebar elasticity modulus *En* (Kpa)	202×10^8
shotcrete elasticity modulus *Eg* (Kpa)	2.19×10^7
Rebar diameter *d* (mm)	25, 28
Overall diameter hole drilling *Ddh* (mm)	100
Nail length *L* (m)	6, 8
Incline angle of soil nail (degree)	15
Nail spaces *Sh* × *Sv* (m×m)	1/5 × 1
Thickness of the shotcrete (mm)	120

Table 2 The geotechnical parameters of the behavioral models

Parameters	HSS model	HS model	MC model
Cohesion *C* (KN/m^2)	1	1	1
Friction angle ϕ	33	33	33
Dilatancy angle ψ	3	3	3
Unit weight of soil (γ) (kN/m^3)	18	18	18
Modulus of elasticity of soil "*E*" (KN/m^2)	22000	–	–
Secant stiffness in standard drained triaxial test stress E_{50}^{ref} (KN/M^2)	–	22000	22000
Tangent stiffness for primary audiometry loading E_{oed}^{ref} (KN/M^2)	–	22000	22000
Unloading/reloading modulus E_{ur}^{ref} (KN/M^2)	–	66000	66000
Reference shear modulus G_0^{ref} (KN/M^2)	–	–	`
Reference stress for stiffness P_{ref} (KN/M^2)	–	100	100
Shear strain as shear modulus at which $0.7G_0$, $\gamma_{0.7}$	–	–	0.0002
Poisson ratio *V*	0.35	–	–
Unloading and reloading Poisson ratio V_{ur}	–	0.2	0.2
Power for stress level dependency of stiffness *m*	–	0.5	0.5

2.1 Mohr-coulomb model

In order to model the behavior of the linear elastic-perfect plastic material, the Mohr-Coulomb model was used along with 5 major parameters. The model applies a combination of Hooker's law and Coulomb's failure criteria. The parameters used in the model are divided into elastic and plastic parameter. The former includes: Young's Modulus (*E*), Poisson ratio (*V*), and the plastic parameters of the model involve soil friction angle (ϕ) and cohesion (*C*) and dilatancy angle (ψ). Calisto *et al*. (1999) demonstrated that the model is endowed with some limitations with respect to the prediction of the displacements prior to the occurrence of failures.

2.2 Hardening Soil model (HS)

The hardening soil model is a robust behavioral model for simulating the behavior of a variety of hard and soft soils (Schanz *et al*. 1999). Among the major characteristics of the model, we can refer to shear and compressive hardening as well as the failure to be stable in the yield level of the model and the change in it as plastic strains go up. As one major difference between hardening soil and Mohr-Coulomb model, we can refer to the stiffness dependent on the strain level of the present model.

The core idea for formulizing this model is the hyperbolic relationship between axial strain and diversionary strain as to triaxial loading. The main parameters of the model include: strength parameters φ and Ψ, *C* as so stiffness parameters: E_{ur}^{ref} and E_{50}^{ref} which can control the behavior of the soil deformation as it is presented in Table 2 earlier, and unloading-reloading reference modulus, E_{ur}^{ref}. The extent to which stiffness is dependent on strain level is determined by the factor m. According to Von Soos (1990), m value is laid in the range of zero to one. The relationship between strain and yield level of hardening model at the space of tridimensional strains is shown in Fig. 1.

2.3 The Hardening Soil model with Stiffness effect ensued from small strains (HSS)

The HSS model that accounts for the increased stiffness of soils at small strains is developed from hardening soil model. According to the researches, the soil materials revealed higher stiffness in small strains. However, this went unnoticed in the most behavioral models such as Mohr-Coulomb and hardening soil model. Benz (2007) considered the effect of the high stiffness

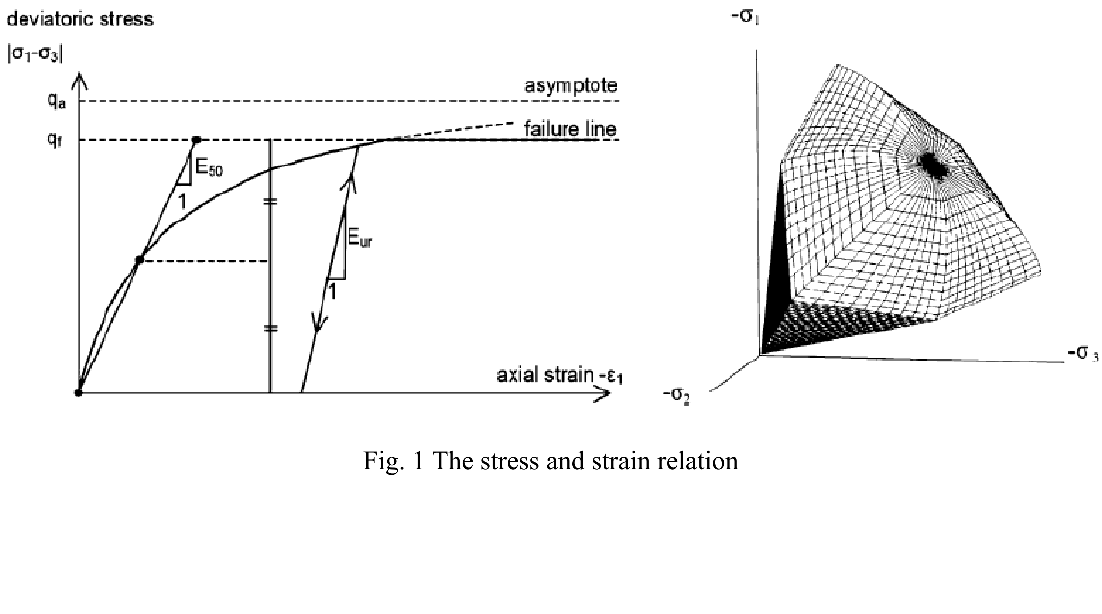

Fig. 1 The stress and strain relation

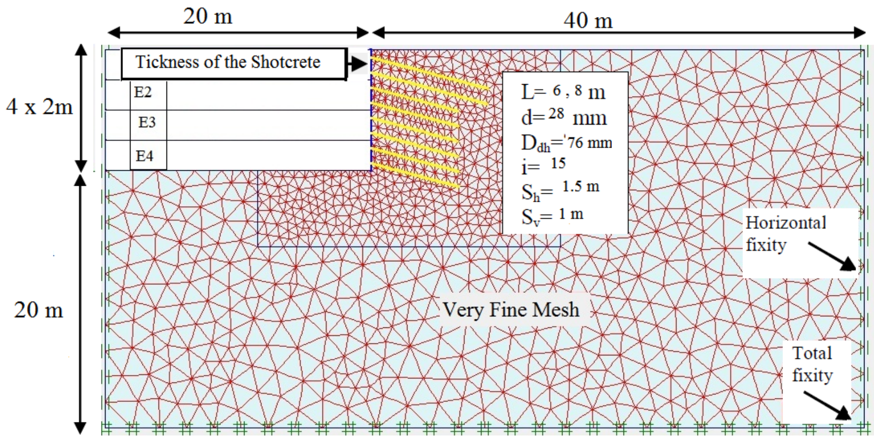

Fig. 2 The scheme of numerical model

of building materials on small strains by making some corrections to the hardening soil. In order to exert the effect of non-linearly raising the stiffness in the strains smaller than engineering strains, the parameters, G_0, $\gamma_{0.7}$ as well as previous parameters were inserted in the HS model, which made the new model called HSS. G_0 consists of initial shear modulus as do $\gamma_{0.7}$ shear strain when shear modulus value reached $0.7G_0$.The main difference between HS and HSS model lies in the application of yield criterion as well as the law of modified flow. Hence the HSS model shows lesser failure strain than HS.

3. Finite element model

To build a model as earlier mentioned, the plane strain conditions were used. The networking was carried out using 15-point grid triangular element. To make overall network, the density, Very fine, was used. The networking became finer as much as one degree around the nails. The Fig. 2 represents the modeled wall along with its dimensions and boundary conditions.

3.1 Nail correspondence parameters

Normally, the plain elements are used for numerically modeling nailing system at the state of plain strain. In practice, different models are used for calculating nail input parameters. It is a correct way to model injected nail system that we use E_{eq} equal elasticity modulus. The equal elasticity modulus is calculated based on considering the elastic stiffness covering the injection as well as interior nail rebar and based on material resistance principles

$$E_{eq} = E_n\left(\frac{A_n}{A}\right) + Eg\left(\frac{Ag}{A}\right) \tag{1}$$

Where E_n stands for the elasticity modulus of interior nail rebar and E_g stands for the elasticity modulus of injected materials as K stands for interior cross rebar and $A = 0.25\pi D^2_{dh}$ equals to the overall area of injected nail system and $A_g = A - A_n$ equals to the injected pure level and E_{eq} equals to the elastic modulus of the injected nails. If we show the horizontal distance between nails by SH, the extent of axial stiffness of the injected nail system is measured by having E_{eq} from the Eq. (1)

$$EA = \frac{Eeq}{S_h}\left(\frac{\pi D_{dh}}{4}\right) \tag{2}$$

3.2 Overall procedure of numerical modeling

- As for the input, the Plaxis geometry software which involved the nails and shotcrete procedures is to be modeled. In what followed, the boundary conditions and the geometry of construction process were defined and material building parameters were inserted. After completing these process, an appropriate finite element networks were selected and prepared to be networked based on this. As it is shown in Fig. 2, the selected network was made finer as much as one degree in order to raise the accuracy of the calculations around the nails. With the completion of building model, k_0 procedure was used for generating sustainable strains. It must be noted that the value of k_0 was considered much the same as $1-\sin\varphi$ based on Jackie's equation.
- Having completed the construction of the model in input, we arrived at the calculation of the software. In this section, the procedure of the stages for defining and analyzing soil excavation and the implementation based on real stages were chosen, in the sense that excavation and in stalment of nailing system and shotcrete procedure were defined within four calculation phases, E_4*to* E_1, as it is shown in Fig. 2. At each stage of construction, one 2-meter layer of the sustainable soil was made inactivated and the nailing system as well as shotcrete procedure would be installed by activating structural elements used for modeling. The type of analysis would be adjusted on plastic calculation mode.
- At the end of each stage, an aim was made to determine the reliability factor related to Phi/C Reduction analysis which is based on the strength reduction.

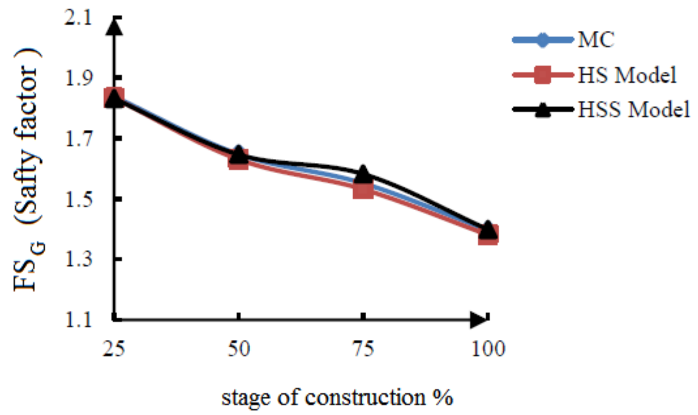

Fig. 3 The overall reliability coefficient of a model at the stage of construction

3.3 Behavioral models and the nailed wall system response

As for the nailed wall systems which were introduced in the Tables 1 and 2 of geometry characteristics and its material, the main aspects of the nailed system behavior were approached by means of the method offered in the previous section. In doing so, three behavioral models which include Mohr-Coulomb (MC), hardening soil model (HS) and hardening soil with the stiffness ensued from small strains (HSS) were used; the obtained results were offered in the following sections.

4. The effect of behavioral models on overall sustainability

The results of the overall reliability factor were offered at each stage of construction by using the three behavioral models offered in Fig. 3. As Fig. 4 suggests, each three models yielded similar results of overall reliability coefficient at different stage, which there is no obvious difference between the values obtained from HS and HSS behavioral model and that of MC.

5. The effect of behavioral models on bed swelling and the horizontal displacement of the nailed wall system

It is indeed of particular significance that there is a control over the displacement of the nailed walls. Because of a failure to protect bottom excavation during construction, unbalanced forces can transform the position of the excavation bottom into one that goes inwardly, which is called bed swelling and known as one of the agents for triggering failure – the failure ensued from bearing capacity (FHWA 2003). Fig. 4 indicates the value of bed swelling or the maximum extent of displacement going inwardly in the excavated section where stands in front of the nailed wall for each stage of construction by using the three diverse behavioral models. From Fig. 5, it can be clearly inferred that MC model could more strikingly estimate the value of bed swelling than HS and HSS; that is to say, such extent may even reach up to two times bigger at some points. The

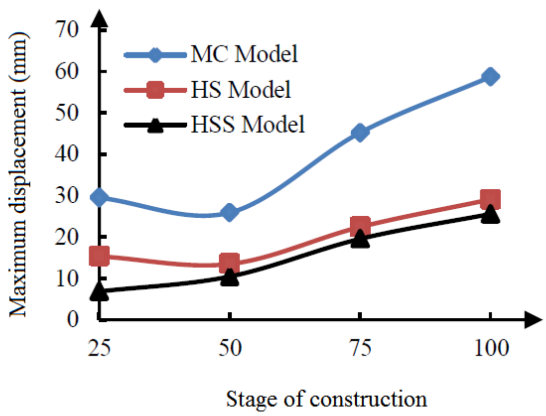

Fig. 4 The maximum upright displacement of bed during construction

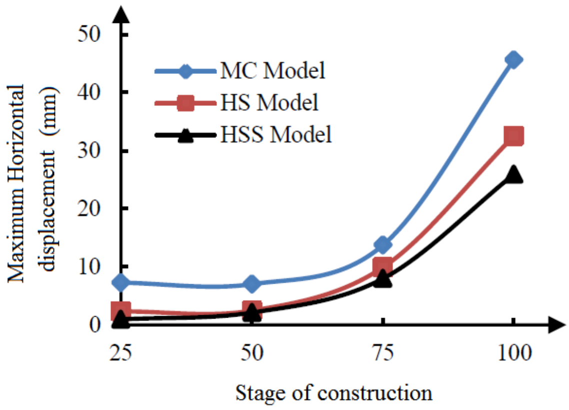

Fig. 5 The maximum horizontal displacement of a model

result of this section was rightly in line with those of the studies offered earlier (Calistou *et al*. 1999, Brinkgreve *et al*. 2006). This is likely related to the assumption of linear behavior prior to yielding as formulizing MC model. Therefore, it can be inferred that the application of powerful behavioral models such as HS or HSS can give more reasonable results than MC model at the time of modeling the nailed walls in soft soils. Moreover, it may be seen that HSS model indicates the extent of bed swelling much lesser than HS model; the issue is related to considering the stiffness intensified in small strains by HSS model (Brinkgreve *et al*. 2006, Benz 2007).

The maximum lateral displacements of the three models were shown at each phase of modeling in Fig. 5. It can be seen that MC model, in this regard, shows the extent of the maximum horizontal displacement greater than the two models, HSS and HS. However, the difference extent is varied at different stages of excavation with each other; that is to say, as Fig. 6 suggests, MC model showed the maximum extent of horizontal displacement about two times greater than HSS model at the end of excavation.

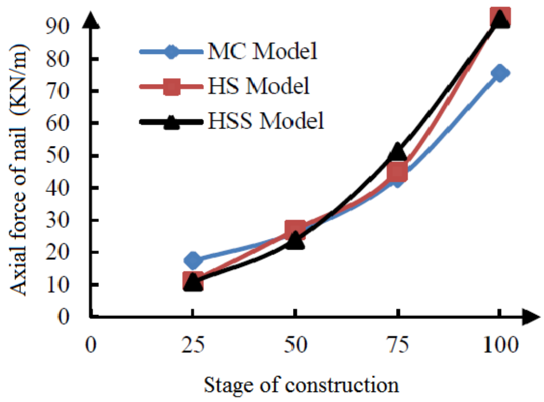

Fig. 6 The maximum axial force of nail with construction stages

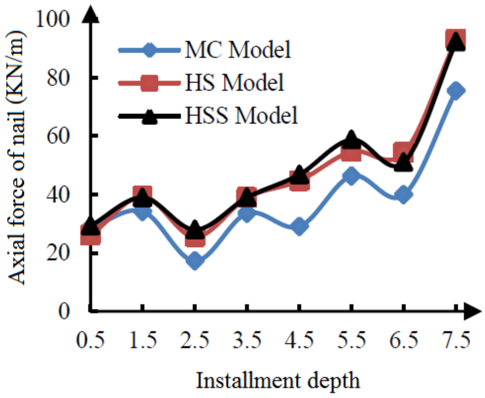

Fig. 7 The maximum axial force of nail with installment depth

6. The effect of behavioral models on axial forces generated in the nails

Figs. 6 and 7 show the maximum extent of the force generated at unit of nail length at different stages of excavation and under different depths of installment respectively.

From Fig. 6, it can be easily realized that each of three behavioral models yields the similar and close results of axial forces generated in the nails at different stages of construction. Moreover, it can be observed that MC model represents axial force fairly lesser than HS and HSS models.

Such trend recurred in Fig. 8 as well. In this figure, it can be clearly seen that MC model gives fewer values in terms of the maximum force generated in the nails. In addition to the maximum axial force generated in nails, series of studies were previously carried out and observed as to bending anchor and the maximum developed axial force of nails by Singh and Babu (2010); in this respect, each of behavioral models would deliver similar results. Therefore, it can be concluded that MC model is endowed with higher ability in predicting the values of the strains generated in the elements concerning numerical calculations than models such as HS and HSS.

7. Conclusions

In this research, the application of behavioral models, HS and HSS, were compared with MC model in terms of numerical simulation of nailed walls.

Using finite elements method and assuming the dominance of plain strain conditions, the results of simulation revealed that the application of advanced behavioral models like HS and HSS makes little difference to MC model in terms of estimating the overall stability coefficient of wall as each of the three models yielded relatively similar results. Such result of estimating the maximum developed force in nails can be obtained. Furthermore, given the results obtained from the resent study, we can state that when very small lateral deformations exert effects on stability and overall deformation of system and also in case of the presence of soft soils in the spot, the application of robust behavioral models seems essential. Moreover, the application of behavioral models such as HS and HSS delivers more appropriate results than that of MC model regarding the prediction of excavation bed swelling.

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