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ORIGINAL PAPER

2D Numerical Simulations of Soil Nail Walls

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Abstract In practice, numerical simulations of soil nail walls are often carried out to assess the performance and stability. In the present study, implications of the use of advanced soil models, such as hardening soil model and hardening soil with small-strain stiffness model to simulate the behavior of in situ soil on the overall response of simulated soil nail wall have been studied, and compared with respect to the analysis using conventional and most prevalently used Mohr-Coulomb soil model. Further, influence of the consideration of bending stiffness of soil nails on the simulation results has been examined. Results of the simulations indicated that the use of advanced models is desirable for cases of soil nail walls constructed in soft soils and when lateral wall displacements are critical to the adjoining structures. Incorporation of bending stiffness of nails is found important from the consideration of facing failure modes of soil nail walls.

Keywords Soil nailing · Finite element · Numerical simulation · Material models · Bending stiffness

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1 Introduction

The performance of soil nail walls is significantly affected due to the complex mutual interaction between its main components—the native soil, the reinforcement (nails) and the facing. Additionally, various other factors such as the construction sequence, the installation method of nails, the connection between the nails and the facing, are also likely to influence the behaviour of the soil nail walls. Conventional soil nailing design procedures (e.g. FHWA 2003) based on limit equilibrium methods fail to address such issues. Consequently, in practice, to study the complex soil-structure interaction and to assess the performance of soil nail walls, often numerical simulations are performed using rigorous computational codes based on numerical techniques such as finite element method (e.g. Smith and Su 1997; Zhang et al. 1999; Fan and Luo 2008), discrete element method (e.g. Kim et al. 1997) and finite difference method (e.g. Sivakumar Babu et al. 2002).

It is well established that the accuracy of numerical simulations depends significantly on the constitutive soil model used (e.g. Brinkgreve et al. 2006) and the selection of the appropriate corresponding model parameters (e.g. Calvello and Finno 2004). Mohr-Coulomb model, being the first order soil model, is most commonly used for numerical simulations in the soil nailing applications (e.g. Kim et al. 1997; Smith and Su 1997; Zhang et al. 1999;

Sivakumar Babu et al. 2002; Fan and Luo 2008). Few researchers have used advanced soil models such as Duncan-Chang hyperbolic model (e.g. Briaud and Lim 1997), SP model—a modified Mohr-Coulomb model incorporating strain softening behavior (Cheuk et al. 2005), Drucker-Prager yield criterion (Ng and Lee 2002) and Hardening soil model (Liew and Khoo 2006) for simulating soil behavior in the numerical modeling of soil nail walls. Brinkgreve et al. (2006) reported that the high stiffness of soils at very small-strains ($<10^{-5}$) may play an important role in the applications such as embankments, foundations and excavations with 'engineering strain levels' ($>10^{-3}$; defined as range of shear strains that can be measured in conventional laboratory tests such as triaxial and oedometer tests without special instrumentation). Benz (2007) developed HSsmall model accounting for the small strain stiffness of the soil. From the observations reported in the literature, it is evident that the use of advanced soil models provides more realistic response of the simulated structures, but at the same time, may require greater capacity of the computational machine, may increase computational time drastically, may need sophisticated geotechnical investigation and demand for more experienced and judicious selection of the model parameters. Thus, it becomes desirable to assess the implications of the use of advanced soil models over conventional Mohr-Coulomb model for any particular application. In the present study, two advanced soil models namely, HS-model (Hardening soil model) and HSsmall model (Hardening soil with small strain stiffness model) are benchmarked with respect to the most prevalently used MC-model (Mohr-Coulomb model) for the numerical simulations of the soil nail walls.

In addition to the above, the present study brings out the implications of the consideration of bending stiffness of nails and finite element mesh density on the simulation results of the soil nail walls. Following section discusses the methodology and the various material parameters adopted for the study.

2 Methodology and Material Parameters

For the purpose of illustration and better understanding, a typical 10 m high soil nail wall with vertical face and horizontal backfill is considered for the study. Design of the soil nail wall is carried out according the allowable stress design procedure given in FHWA (2003). Table 1 summarises the geometric configuration and other design details of the soil nail wall. PLAXIS (2006) is used to carry out the finite element based simulations of the soil nail wall considering it as a plane strain problem and accounting for the long term behaviour using drained conditions. Numerical simulations of the soil nail wall are performed considering MC-model, HS-model and HSsmall soil models and observations are made regarding global stability, displacements of the excavation base, lateral deformations and axial forces in the nails after each construction stage. Given below is the brief description about the various model parameters required in MC-model, HS-model and HSsmall soil models used to simulate soil nail wall. Primary objective of the study being to bring out the implications of the use of different soil models, typical values of the various soil model parameters for the study are adopted from Brinkgreve et al. (2006) and are summarised in Table 2.

2.1 Mohr-Coulomb Model (MC-model)

MC-model is an elastic perfectly plastic model, which combines Hooke's law and the Coulomb's failure criterion. It is a first order model for soils which requires the five basic input parameters namely Young's modulus E and Poisson's ν for soil elasticity,

Table 1 Soil nail wall geometry and other parameters

Parameter	Value
Vertical height of the wall H (m)	10.0
Face batter α (deg)	0.0
Backslope angle β (deg)	0.0
Nailing type	Grouted
Grouted nails and facing	
Material model	Elastic
Yield strength of reinforcement f_y (MPa)	415.0
Elasticity modulus of reinforcement E_n (GPa)	200.0
Elasticity modulus of grout (concrete) E_g (GPa)	22.0
Diameter of reinforcement d (mm)	20.0
Drill hole diameter D_{DH} (mm)	100.0
Length of nail L (m)	7.0
Inclination wrt horizontal i (deg)	15.0
Spacing $S_h \times S_v$ (m × m)	1.0 × 1.0
Facing thickness t (mm)	200.0

Table 2 Soil model parameters (Bringreve et al. 2006)

Parameter	MC	HS	HSsmall
Cohesion c (kN/m^2)	10.0	10.0	10.0
Friction angle φ (deg)	27.5	27.5	27.5
Dilatancy angle ψ (deg)	0.0	0.0	0.0
Unit weight γ (kN/m^3)	19.0	19.0	19.0
Modulus of elasticity of soil E (kN/m^2)	30,000	–	–
Secant stiffness in standard drained triaxial test E_{50}^{ref} (kN/m^2)	–	20,000	20,000
Tangent stiffness for primary oedometer loading E_{oed}^{ref} (kN/m^2)	–	20,000	20,000
Unloading/reloading stiffness E_{ur}^{ref} (kN/m^2)	–	60,000	60,000
Reference shear modulus G_0^{ref} (kN/m^2)	–	–	75,000
Reference stress for stiffness p_{ref} (kN/m^2)	100.0	100.0	100.0
Shear strain at which $G_{secant} = 0.7\ G_0$, $\gamma_{0.7}$	–	–	0.0001
Poisson's ratio v	0.3	0.2	0.2
Power for stress level dependency of stiffness m	–	0.5	0.5

For HS and HSsmall models $v = v_{ur}$ (unloading–reloading)

soil friction angle φ and soil cohesion c for soil plasticity, and the dilatancy angle ψ. Since the pre-failure stiffness behavior is assumed to be linear elastic, the model has a limitation in terms of prediction of the deformation behavior before failure (Callisto et al. 1999).

2.2 Hardening-Soil Model (HS-model)

Schanz et al. (1999) provides information about the formulation, various model parameters and verification of HS-model. It is an advanced soil model capable of simulating both soft and stiff soils. Similar to MC-model, failure in HS-model is defined by means of Mohr-Coulomb failure criterion. Unlike the MC-model, the HS-model accounts for the increase in stiffness with pressure. The model uses a power law formulation for stress-dependent stiffness similar to the one used in the Duncan-Chang hyperbolic model (Duncan and Chang 1970). The HS-model requires 11 input parameters, i.e. three reference stiffness parameters; the triaxial loading stiffness E_{50}, the triaxial unloading stiffness E_{ur} and the oedometer loading stiffness E_{oed}. A power m parameter for the stress-dependent stiffness formulation, a Poisson's ratio for loading and unloading v_{ur}, the Mohr-Coulomb strength parameters φ and c, the dilatancy angle ψ, a K_0-value, and a parameter called the failure ratio R_f which determines the strain level at failure and p^{ref} a reference stress for stiffnesses.

2.3 Hardening-Soil with Small Strain Stiffness Model (HSsmall model)

The HSsmall model (Benz 2007) is a modification of the Hardening Soil model that accounts for the increased stiffness of soils at small strains. At low strain levels most soils exhibit a higher stiffness than at engineering strain levels; this stiffness varies non-linearly with strain. This behaviour is described in the HSsmall model using two additional strain-history material parameters: (a) the initial or very small-strain shear modulus G_0 and (b) the shear strain level $\gamma_{0.7}$ at which the secant shear modulus G is reduced to 70% of G_0.

3 Finite Element Simulations

As mentioned earlier, soil nail wall is modeled as a plane strain problem and long term behavior is simulated using drained analysis conditions. 15-noded triangular elements are used for generating finite element mesh of appropriate density. Coarse mesh density is adopted globally, which is refined to fine density in the vicinity of the soil nail wall (Fig. 1). Mesh boundaries are placed far enough so as to minimise the influence of mesh boundaries on the results of the numerical simulation (Briaud and Lim 1997). Figure 1 shows the simulated soil nail wall with dimensions and various parameters including in

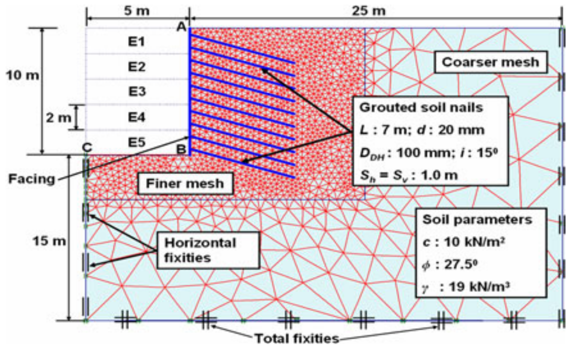

Fig. 1 Numerically simulated 10 m high soil nail wall

situ soil properties, mesh boundaries and fixity conditions.

3.1 Equivalent Nail Parameters

Most commonly, in the plane strain simulation of the soil nail walls; rectangular shaped structural elements are used to simulate soil nails. Depending upon whether in the numerical simulations the bending stiffness of soil nails is to be considered or not, the most important input material parameters for the structural elements simulating soil nails are the axial stiffness *EA* and/or the flexural rigidity (bending stiffness) *EI*. In practice, *plate* structural elements or *geogrid* structural elements (which only require the axial stiffness *EA* as input) are being used for soil nail wall simulations using Plaxis. Both the plate and geogrid structural elements are rectangular in shape with width equal to 1 m in out-of-plane direction. Since, the soil nails are circular in cross-section and placed at designed horizontal spacing, it is necessary to determine equivalent axial and bending stiffnesses for the correct simulation of circular soil nails as rectangular plate structural elements.

For the grouted nails, equivalent modulus of elasticity E_{eq} shall be determined accounting for the contribution of elastic stiffnesses of both grout cover as well as reinforcement bar. From the fundamentals of strength of materials, E_{eq} can be determines as

$$E_{\mathrm{eq}} = E_n\left(\frac{A_n}{A}\right) + E_g\left(\frac{A_g}{A}\right) \tag{1}$$

where: E_g is the modulus of elasticity of grout material; E_n is the modulus of elasticity of nail; E_{eq} is the equivalent modulus of elasticity of grouted soil nail; $A = 0.25\pi D_{\mathrm{DH}}^2$ is the total cross-sectional area of grouted soil nail; $A_g = A - A_n$ is the cross-sectional area of grout cover; $A_n = 0.25\pi d^2$ is the cross-sectional area of reinforcement bar and D_{DH} is the diameter of drill hole. If, S_h is horizontal spacing of soil nails, knowing the equivalent modulus of elasticity E_{eq} (Eq. 1) for the grouted soil nail, the axial and bending stiffnesses can be determined using Eqs. 2 and 3, respectively.

$$\text{Axial stiffness EA } [\mathrm{kN/m}] = \frac{E_{\mathrm{eq}}}{S_h}\left(\frac{\pi D_{\mathrm{DH}}^2}{4}\right) \tag{2}$$

$$\text{Bending stiffness EI } \left[\mathrm{kNm^2/m}\right] = \frac{E_{\mathrm{eq}}}{S_h}\left(\frac{\pi D_{\mathrm{DH}}^4}{64}\right) \tag{3}$$

3.2 General Procedure for Numerical Simulation

Given below are the general steps followed in the numerical simulation of the soil nail wall.

- In the input program, geometry of the soil nail wall (including nails and facing elements layout), boundary conditions, construction stages, material properties are defined. This is followed by the generation of finite element mesh with desired mesh density and initial gravity stresses using K_0-procedure (i.e. at-rest condition).
- Accomplishment of physical modeling in the input program is followed with the calculation program. Staged construction option is used to simulate cconstruction of the soil nail wall in five stages indicated as E1, E2,…,E5 in Fig. 1. In each construction stage, excavation depth of 2 m in situ soil is simulated by deactivating the corresponding soil cluster and the installation of nail and facing is performed by activating the corresponding structural element. Calculation type was set to the “plastic analysis”.
- After each excavation stage, factor of safety for global stability is determined using “Phi/c reduction” option as the calculation type. In the Phi/c reduction or strength reduction technique (Matsui and San 1992) critical failure mechanism is identified automatically, which is normally assumed in the conventional analysis. Dawson et al. (1999) showed that the factors of safety calculated from this approach are very close to the values obtained from conventional methods in geotechnical analysis. They also indicated that

this method is more general and flexible and it is more advantageous particularly when the failure mechanism is complex as in the case of soil nail walls.

4 Soil Models and Response of Soil Nail Wall

For the soil nail wall defined by parameters given in Tables 1 and 2, and using the methodology presented earlier; various important aspects of the soil nail walls are studied. Observations are made from the numerical simulations of the soil nail wall using different material models namely MC-model, HS-model and HSsmall model, and are discussed in the following sub-sections. It is worth mentioning that for the same finite element mesh density and geometric parameters, the overall calculation time for the numerical simulation of the soil nail wall increased to about 4–5 times by the use of HS-model and to about 9–10 times by the use of HSsmall model in comparison to the MC-model.

4.1 Influence of Material Models on Global Stability

Figure 2 shows the trend in the variation of the factor of safety for global safety with construction stages of the soil nail wall simulated using three different material models. From Fig. 2, it is evident that all the three material models capture similar response. In other words, use of advanced soil models has negligible influence on the evaluation of global stability of the soil nail wall using numerical simulations.

4.2 Influence of Material Models on Base Heave of Excavation

FHWA (2003) identifies basal heave or bearing capacity failure as one of the external failure mode for soil nail walls. This failure mode may be of concern when a soil nail wall is excavated in soft soils. Because the wall facing does not extend below the bottom of the excavation, the unbalanced load due to the excavation may cause the bottom the excavation to heave and stimulate a bearing capacity failure of the foundation. Figure 3 shows upward heave or the displacement of the excavated soil in front of the soil nail wall face with construction stages for the soil nail wall simulated using three different material models. For each construction stage, base heave shown in Fig. 3 is the maximum value of the vertical upward displacement of excavation base BC (see Fig. 1). From Fig. 3, it is evident that MC-model over-estimates the base heave of the excavation face to almost twice as that predicted by HS-model or HSsmall model. This observation regarding over-prediction of base heave is in good agreement with literature (e.g. Callisto et al. 1999; Brinkgreve et al. 2006) and may be attributed to the consideration of linear elastic pre-failure soil behavior assumed in MC-model formulation. Thus, whenever, soil nailing walls in soft soil conditions are numerically

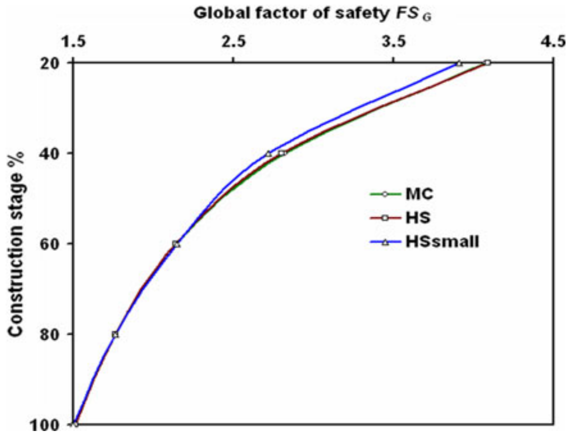

Fig. 2 Global factor safety of soil nail wall with construction stage

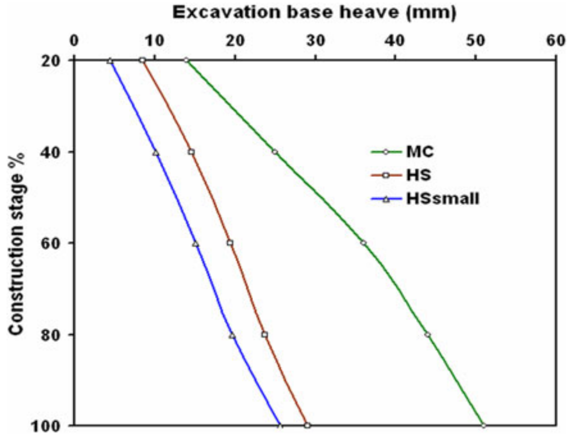

Fig. 3 Excavation base heave with construction stage

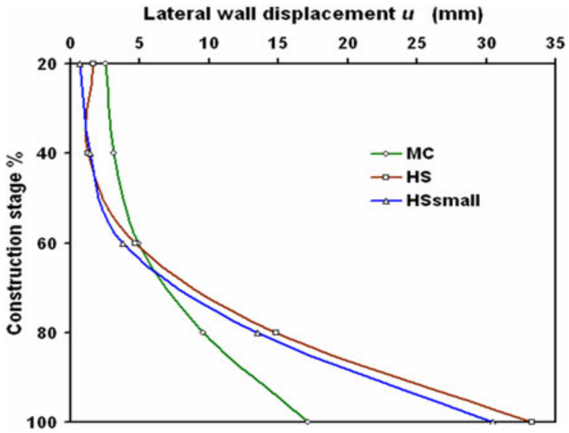

Fig. 4 Lateral displacement of soil nail wall with construction stage

simulated, it is advisable to use advanced models such as HS-model or HSsmall model in-lieu of MC-model. The above aspect may also be useful from the consideration of stability of soil nail walls during construction stages. HSsmall model predicts excavation heave even lesser than HS-model (though not very significantly) attributing to the role of increased stiffness of soils at very small strains (Brinkgreve et al. 2006; Benz 2007).

4.3 Influence of Material Models on Lateral Displacement of Soil Nail Wall

Figure 4 shows the maximum lateral displacement of the soil nail wall with construction stages for the soil nail wall simulated using three different material models. For each construction stage, lateral displacement shown in Fig. 4 is the maximum value of the horizontal displacement (which usually occurs at top) of vertical wall face AB (see Fig. 1). It may be observed from the Fig. 4 that up to 60% of the construction stage, lateral displacements of soil nail wall predicted by MC-model are more than (though not very significantly) those predicted by HS-model or HSsmall model. However, beyond 60% construction stage, maximum lateral displacements of the soil nail wall predicted by MC-model are significantly less (almost 50% less for the fully constructed soil nail wall i.e. 100% construction stage) than those predicted by HS-model or HSsmall model. These observations may be attributed to the following two reasons: (a) that with the increasing construction stages, cumulative plastic strains in the soil nail system increase and thereby reduce the stiffness of the retained soil mass significantly, and (b) assumption of the linear elastic pre-failure behaviour of the soil in MC-model.

4.4 Influence of Material Models on Axial Force Development in Soil Nails

Figures 5 and 6 show the maximum axial tensile forces developed in the soil nails with construction stages of the soil nail wall and with the depth of embedment of the soil nails, respectively. The soil nail force in Fig. 5 is the maximum axial force developed among the nails installed up to the construction stage in consideration, whereas, the soil nail force in Fig. 6 is the maximum axial force developed in a given nail along its length. From Fig. 5, it is evident that all the three soil models used in the study predicts almost similar response of the maximum axial force developed in soil nails with construction stages. However, it may be noted that the MC-model underestimates the axial force developed in the soil nails. Similar observations can be made from Fig. 6 regarding the development of axial force in the soil nails embedded at different depths. The dashed line in Fig. 6 shows the theoretical value of the maximum axial force $T_{\max}$ in a nail embedded at depth z below ground surface obtained using expression: $T_{\max} = K_a \gamma z S_h S_v$, where K_a is the active earth pressure coefficient (FHWA 2003). This expression

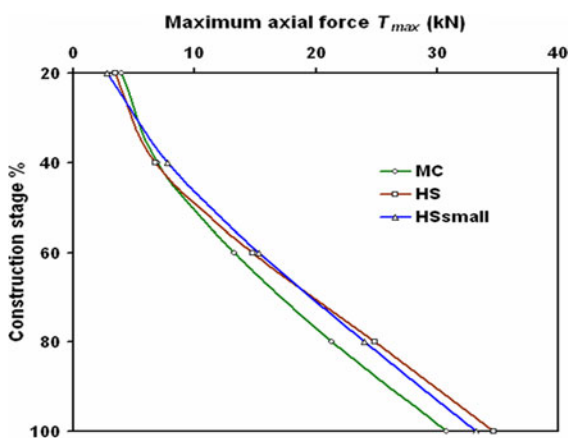

Fig. 5 Development of maximum axial force in nails with construction stage

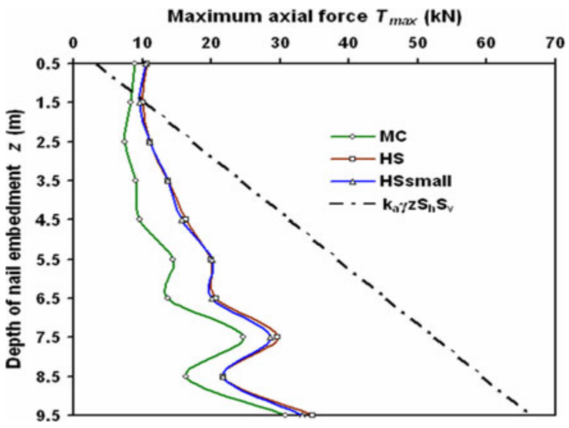

Fig. 6 Variation of maximum axial force in nails with embedment depth (100% CS)

is based on the concept that a soil nail embedded at depth z below ground surface is subjected to a maximum lateral earth pressure $K_a\gamma z$ acting on a nail influence area defined by the product of the vertical and horizontal nail spacings (i.e. nail influence area = S_hS_v). Since, the theoretical evaluation of the axial force in nails embedded at different depths do not account for the load re-distribution due to the construction stages, the theoretically expected axial forces are found to be considerably more than the computed axial forces (see Fig. 6). In addition to the development of axial force, observations were made regarding the development of maximum bending moments and the maximum shear forces in nails and it is found that use of different soil models does not have any considerable influence. Thus, in general, MC-model can be considered capable of capturing the response of stress elements in soil nails reasonably accurately.

5 Role of Bending Stiffness of Soil Nails

Incorporation of bending and shear resistances of nails in the analysis and design of soil nail walls had been a much debatable issue reported in the literature. For example, Juran et al. (1990) reported that inclined nails (10–15^0) would tend to undergo a local rotation to approach the horizontal direction of maximum soil extension, and therefore, the effect of bending stiffness has significant effect on the development of nail forces. Schlosser (1991), based on his multicriteria theory in soil nailing and observations from the extensive experiments (such as national research project Clouterre) and other works related to soil nailed retaining structures in France over 10 years, stated that, at failure bending and shear resistances of grouted nails are mobilised, however, the influence of bending stiffness and shear on the global safety factor is small (less than 15%). Jewell and Pedley (1992) concluded that the effects of bending and shear resistances can be ignored in the design and analysis of soil nailing with marginal conservatism. In practice, ignoring the effects of shear and bending resistances of soil nails, soil nailing analysis and design has been radically simplified and this approach is commonly accepted (e.g. FHWA 2003).

In practice, bending stiffness of the soil nails is often considered in the numerical simulations of the soil nail walls (e.g. Fan and Luo 2008). On the other hand, few researchers prefer to ignore the contribution of bending and shear capacity of soil nails in the analysis (e.g. Liew and Khoo 2006). In the light of fact that consideration of bending and shear resistance of soil nails is conservatively ignored in the conventional analysis and design of soil nail walls, it is found desirable to study the implications of the consideration of bending stiffness of soil nails on the analysis of the soil nail walls. As mentioned previously, plate structural element in Plaxis can be used to perform analysis of soil nail walls considering bending stiffness of soil nails as they require both axial stiffness EA and bending stiffness EI as the main material parameters. On the other hand, geogrid structural elements can be used to model soil nails with considering bending stiffness of soil nails as they require only axial stiffness EA as the main input parameter.

In order to study the implications of the consideration of bending stiffness of soil nails in analysis of soil nail walls based on numerical simulations, two series of simulations of the soil nail wall of 10 m height are performed, one with the use of plate structural elements to simulate soil nails and the other with the use of geogrid structural elements to simulate soil nails. Various material properties and other parameters indicated in Tables 1 and 2 are used and soil behaviour is simulated using MC-model. At each construction stage of the wall, observations are made with regard to the global factors of safety, maximum lateral (horizontal) displacement of walls, maximum axial tensile developed and development of bending moment and shear force in nails (for plate elements only). Response corresponding to the consideration of bending stiffness is indicated by “Plate” and ignoring bending stiffness is indicated by “Geogrid” in the plots of the observations form numerical simulations.

Figure 7 shows the trend of variation of global factor of safety of the soil nail wall with construction stage. It is evident from Fig. 7, that for the fully constructed soil nail wall (i.e. 100% construction), consideration of bending stiffness of nails in the analysis has negligible influence on the global stability. However, it is worth noting from the Fig. 7 that consideration of bending stiffness of nails in the analysis has significant influence during the construction stage. Geogrid structural elements resulted in significantly less factors of safety for global stability in comparison to the plate structural elements. Alternatively, it can be interpreted that bending stiffness plays important role in the stability of soil nail walls during the construction stage.

Figure 8 shows the trend of maximum lateral displacements of the soil nail wall with construction stage. It is evident from Fig. 8 that the almost similar displacement response is captured by both geogrid elements and plate elements. This implies that the consideration of bending stiffness has negligible influence on deformation analysis of the analysis of soil nail walls.

Figures 9 and 10 show the development of maximum axial force in nails with construction stage. From Figs. 9 and 10, it can be observed that on an

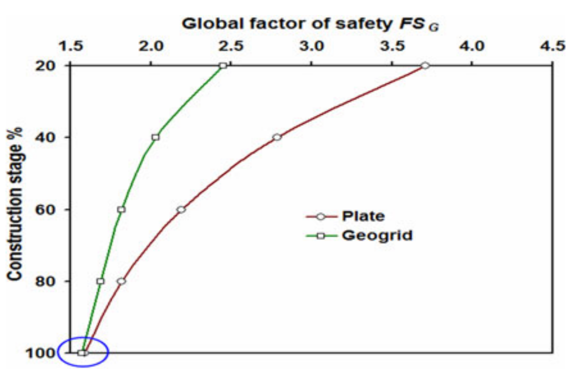

Fig. 7 Trend of global factor of safety of soil nail wall with construction stage

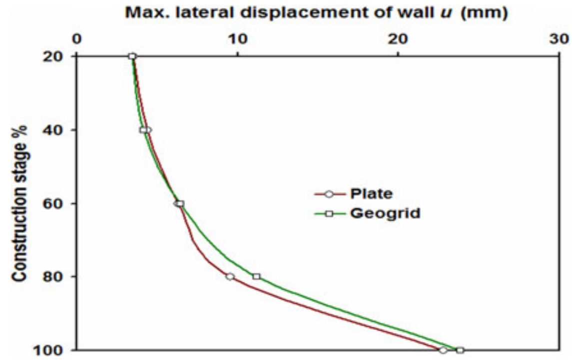

Fig. 8 Trend of lateral displacements of soil nail wall with construction stage

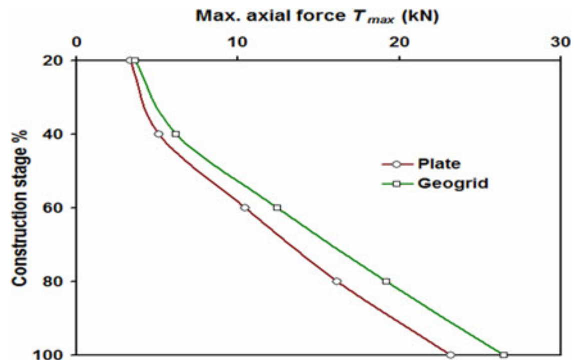

Fig. 9 Development of maximum axial force with construction stage

average the maximum axial force developed in nails simulated using geogrid elements is found to be 15% more in comparison to that developed in nails using plate elements. In other words, lesser axial developed in nails simulated using plate elements may be credited to the contribution of bending stiffness of the nails. This observation is in good agreement with the literature (Schlosser 1991). Figure 11 shows the variation of axial force along the nail length for nails embedded at different levels. Very close resemblance among the axial forces variation along nail length is evident from Fig. 11 for the nails simulated using geogrid and plate elements.

Development of maximum bending moment and maximum shear force in nails with construction stages are shown in Fig. 12. It is evident from Fig. 12 that bending and shear capacities of soil nail start mobilising with increasing construction stages.

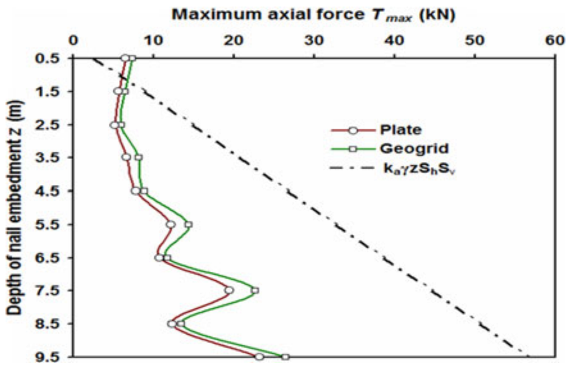

Fig. 10 Maximum axial force developed in nails with embedment depth (100% CS)

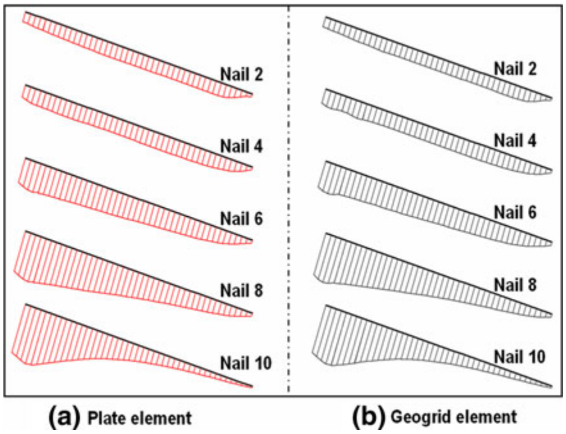

Fig. 11 Variation of axial force along nail length (alternate nails shown)

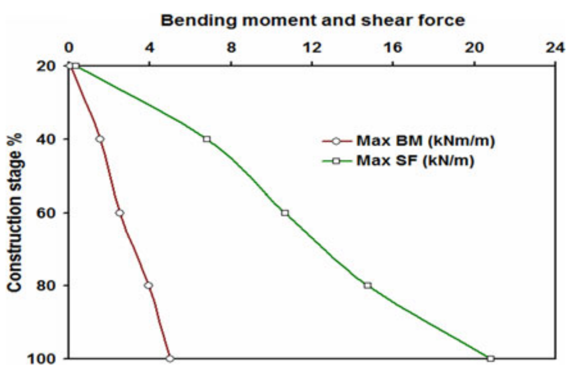

Fig. 12 Development of maximum bending moment and maximum shear force in nails with construction stage

Figure 13 shows the variation of bending moments and shear forces along the nail length for nails embedded at different levels. It is interesting to note

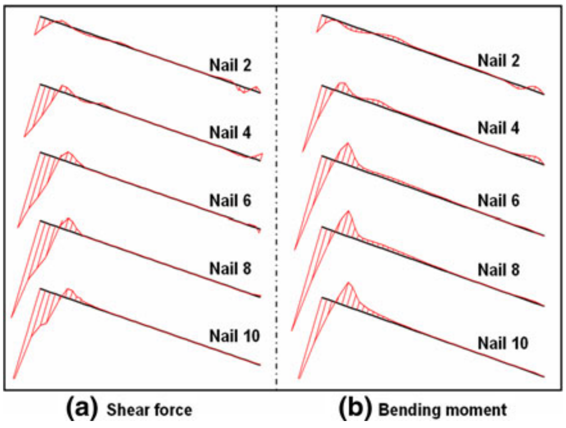

Fig. 13 Variation of shear force and bending moment along nail length (alternate nails shown)

that bending moments and shear forces are concentrated near the face of the wall. This provides an insight into the facing failure modes of the soil nail walls. Generally, soil nail are rigidly connected with the facing and in such cases it is desirable to evaluate the facing design. Improper design may lead to the bending and/or shear failures of soil nails at or near the facing. Ignoring bending stiffness of soil nails may overlook this practical aspect of the soil nail wall analysis completely.

Thus, from the above observations it is apparent that the consideration of bending stiffness of soil nails provides better insight into the analysis of soil nail walls using finite element simulations. Since, finite elements simulations are often performed to investigate the cause of failure or to assess the performance of soil nail walls, it is desirable that bending stiffness shall be considered in the simulations, despite the fact that it is conservatively ignored in the conventional design procedures.

6 Influence of Mesh Density on Numerical Simulations

Another important aspect of the numerical simulation of any structure is the density of finite element mesh adopted. To study the influence of mesh density on the analysis of the soil nail wall, numerical simulations are performed adopting mesh densities ranging from very coarse to very fine, and the results corresponding to the analysis are presented in

Table 3 Influence of mesh density on finite element simulation

Mesh density	Elements per unit volume	Global factor of safety *FS*	Max. hzl. displacement (mm)	Calculation time normalised wrt medium mesh density
Very coarse	0.39	1.610	20.93	0.46
Coarse	0.60	1.598	22.31	0.61
Medium	0.98	1.592	22.86	1.00
Fine	2.08	1.553	24.79	2.24
Very fine	4.14	1.521	28.35	6.18

FS values correspond to the fully constructed wall. If *FS* is to be determined after each construction stage, calculation time may vary even more drastically

Table 3. It is to be noted that this analysis is performed using MC-model. From Table 3, it can be observed that global factor of safety varies significantly from 1.61 for very coarse mesh to 1.52 for very fine mesh. Also, maximum lateral displacements varied from 20.93 mm for very coarse mesh to 28.35 mm for very fine mesh. Similar trends are observed for the stress parameters in nails such as development of axial force, bending moment and shear force. Though, denser mesh may result in more accurate analysis, it is important to note that increasing the mesh density results in drastic increase in the overall calculation time (see Table 3). Thus, appropriate mesh density shall be used depending upon the degree of accuracy required and the capacity of the computing machine. In general, coarse mesh density globally and fine mesh density in the vicinity of the soil nail wall may be used.

7 Concluding Remarks

This study provides a comparison of the use of advanced soil models such as HS-model and HSsmall model in lieu of the most prevalently used MC-model in the numerical simulations of soil nail walls. Implications of the consideration of bending stiffness of soil nails in the analysis using computational tools have also been brought out. Results of the finite element based plane strain simulations of a typical soil nail wall indicate that the advanced soil models considered in the present study have nominal influence on the overall soil nail wall stability analysis and the development of stress elements such as axial forces, bending moments and shear forces in the soil nails. However, in agreement with the literature, use of advanced soil models is found to be essential when very small lateral displacement of the soil nail wall is likely to influence the stability and deformation requirements. Also, when soil nail walls are founded in soft soils, contrary to MC-model, use of advanced soil models provides more appropriate estimate of the basal heave of the excavation. Considering the importance of the selection of suitable model parameters and drastic increase in the calculation time in case of advanced soil models, for general practical applications where lateral displacements are not critical, use of MC-model is found reasonable for the numerical simulations based analysis of soil nail walls.

Since, often computational tools are employed to assess the stability and performance of the soil nail walls, results of the present study indicate that consideration of the bending stiffness of soil nails in the numerical simulations of soil nail walls may provide better insight into the facing failure modes and is found significant during the construction stage. Further, influence of mesh density on the numerical analysis of soil nail walls is studied and use of appropriate finite element mesh density is highlighted.

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