Simulation of Soil Nail Structures using PLAXIS 2D

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Soil nailing is an in-situ earth retaining technique and it has been excessively used all over the world for the various slope stability applications. The efficiency of soil nail structures is the resultant of complex soil-structure interaction among its various components, namely, in-situ soil, stiff reinforcement (i.e nails) and the facing. Often rigorous computational techniques based on finite element or finite difference methods are employed to study the complex soil-structure interaction and to assess the performance and stability of soil nail structures. PLAXIS 2D has been comprehensively used for the study of soil nail structures (e.g. Shiu et al. 2006; Fan and Luo 2008).

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Often rigorous computational techniques based on finite element or finite difference methods are employed to study the complex soil-structure interaction and to assess the performance and stability of soil nail structures. PLAXIS 2D has been comprehensively used for the study of soil nail structures (e.g. Shiu et al. 2006; Fan and Luo 2008).

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).

It has been noted from the literature related to the use of PLAXIS 2D for the study of soil nail structures that users are using both geogrid (e.g. Plaxis 2002; Liew and Khoo 2006) and plate (e.g. Babu and Singh 2007; Fan and Luo 2008) structural elements to simulate nails. It is to be noted that the use of geogrid structural elements completely ignores the bending stiffness the soil nails, on the other hand, plate structural elements accounts for the same. This article provides an insight into the implications of the analysis of the soil nail structures by the use of geogrid (or plate) structural elements for simulation of nails. Additionally, a few suggestions are being made for the proper simulation of soil nail walls using PLAXIS 2D, which may be beneficial to the soil nailing practitioners.

Simulations of soil nail structures using PLAXIS 2D

Simulation of soil nail structures using PLAXIS 2D is time efficient and relatively easy due to the user friendly environment. However, given the capability of the computational tool, the accuracy of the analysis is significantly dependant on the user's understanding about the computational tool and the problem itself. Following are some of the suggestions based on the literature and authors' experiences related to the use of PLAXIS 2D for simulations and analyses of soil nail structures.

Connection of soil nails to the wall facing

In practice, a soil nail is rigidly connected to the wall facing (FHWA 2003; Joshi 2003) by means of bearing plate and hexagonal nut to the temporary facing which in turn is connected with permanent facing using headed studs via bearing plate forming a rigid connection with the continuous reinforced concrete permanent facing. In PLAXIS 2D, connection between two plate structural elements by default represents a rigid connection. Therefore, use of plate structural elements to simulate soil nails and wall facing is recommended to account for the rigid nail-facing connection.

Mesh density, boundaries and fixity conditions

15-node triangular elements can be used for generating finite element mesh. PLAXIS 2D offers choice of mesh density ranging from very coarse to very fine. A detailed discussion on the implications of mesh density on the analysis of soil nail structures has been presented in the later part of the article.

Briaud and Lim (1997) provided information about where to place the boundaries so that their influence on the results of the numerical simulation of soil nail wall can be minimised. They suggested that bottom of the mesh is best placed at a depth where soil becomes notably harder (say at a depth D below the bottom of the excavation). Based on the studies of Briaud and Lim (1997), if D is not

exactly known, D can be taken as two to three times the vertical depth of excavation H. Further, for known values of D and H, width of excavation W_e can be taken equal to three to four times D and the horizontal distance from wall face to the end of mesh boundary B_e can be chosen equal to three to four times ($H + D$). Figure 1 shows the mesh boundaries and fixity conditions.

Material models

Most commonly used material model to simulate in-situ soil for excavation and retaining structures applications is the HS-model (Hardening soil model). However, if all the input parameters for HS-model are not available, alternatively Mohr-Coulomb material model can be used. Facings and nails can be modeled as elastic materials.

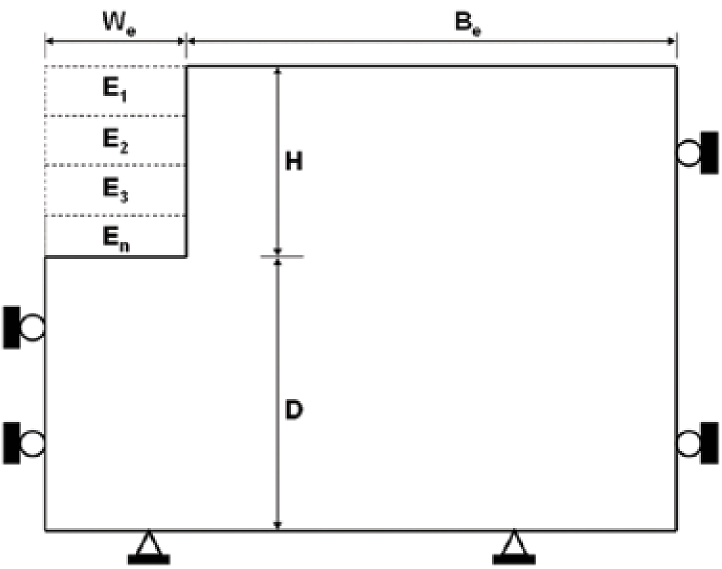

Figure 1: Mesh boundaries and fixity conditions (Briaud and Lim 1997)

Use of interface elements

It has been reported in the literature that the coefficient of soil-reinforcement interaction obtained from field pullout tests (e.g. Wang and Richwein 2002) is found to be significantly more than unity. Therefore, use of interface elements between nail and soil can be eliminated and default setting of "Rigid Interface" in material sets menu for soil and interfaces can be used in the simulation process.

Equivalent nail parameters

Soil nail structures are modeled as plane strain problem in PLAXIS 2D. As stated earlier, plate (or geogrid) structural elements can used to simulate nails. The most important input material parameters for plate elements are the flexural rigidity (bending stiffness) EI and the axial stiffness EA (for geogrid structural element only the axial stiffness EA is required). Both 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 or geogrid elements. A detailed discussion on the suitability of plate or geogrid structural elements to model soil nails is presented later, given below is the general procedure to determine equivalent material parameters.

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:

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

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; $A = 0.25\pi D_{DH}^2$ 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} (equation 1) for the grouted soil nail, the axial and bending stiffnesses can be determined using equations (2) and (3) respectively.

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

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

Substituting, EA and EI values in the material properties menu for Plate elements, PLAXIS automatically determines the equivalent plate thickness in meter d_{eq} using equation (4).

$$d_{eq} = \sqrt{12\left(\frac{EI}{EA}\right)_p} \tag{4}$$

Procedure for numerical simulations

PLAXIS (2006) and the information available in leterature (e.g. Shiu et al. 2006; Fan and Luo 2008) may be referred for the understanding of simulations of soil nail walls with complex geometry and loading conditions.

Staged construction option shall be used to simulate the infuence of construction sequence of soil nail walls (indicated as E_1, E_2, $\ldots E_n$, in Figure 1). In each excavation stage, soil cluster representing excavation lift (defined in input program) is deactivated and nails (modeled as plate or geogrid elements) and facing (modeled as plate element) shall be activated. This procedure can be followed till finish livel of the soil nail wall is reached.

Updated mesh analysis

In order to take into account the effects of large deformations, PLAXIS 2D provides an optional 'Updated Mesh' analysis to perform basic types of calculations (Plastic calculation, Consolidation analysis, Phi-c reduction). Results of the finite element simulation of the 10 m high soil nail wall using 'Updated Mesh Analysis' are indicated in Table 1. Material properties and other soil nail wall parameters adopted are given in Table 2.
It may be observed from Table 1 that the use of 'Updated Mesh' results in marginal influence on the soil nail wall simulation results. Additionally, updated mesh analysis increases the calculation time significantly. Similar observations are made for the 18 m high soil nail wall.

Parameters	Using plate elements		Using geogrid elements	
	Normal analysis	Updated mesh analysis	Normal analysis	Updated mesh analysis
Global factor of safety	1.59	1.60	1.57	1.59
Max. lateral discplacement (mm)	22.82	22.28	23.86	21.31
Max. axial force (kN/m)	74.82	73.29	85.44	83.80

Table 1: 'Update Mesh Analysis' of soil nail wall simulation (H = 10 m)

Parameter	Value
Vertical height of walls H [m]	10.0 and 18.0
Nailing type	grouted
Simulation model	plane strain
Element type	15- node
In-situ soil	
Material model	Mohr-Coulomb
Cohesion c [kPa]	4.0
Internal friction angle ϕ[deg]	31.5
Unit weight γ [kN/m^3]	17.0
Elasticity modulus E_s [MPa]	20.0
Poison's ratio of soil υ_s	0.3
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 (25.0)
Drill hole diameter D_{DH} [mm]	100.0
Length of nail L [m]	7.0 (13.0)
Declination wrt horizontal i [deg]	15.0
Spacing S_h x S_v [m]	1.0 x 1.0
Facing thickness t [mm]	200.0

Table 2: Parameters adopted for numerical simulations using PLAXIS 2D
Note: Figures in bracket correspond tot he 18 m high soil nail wall; all other parameteres are same for both 10 m ad 18 m soil nail walls.

Study on the use of "plate" or "geogrid" elements for simulating soil nails

As brought out earlier, in practice, both plate and geogrid structural elements are being used to simulate soil nails in modelling of soil nail structures using PLAXIS 2D. In the light of fact that consideration of bending and shear resistance of soil nails is conservatively ignored in the analysis and design of soil nail structures, suitability of using plate or geogrid structural element in modelling soil nails has been examined.

Two soil nail walls of 10 m and 18 m vertical height designed conventionally with reference to FHWA (2003) are considered for the study. Two different heights of soil nail walls are selected for the analysis so that a comparison can be made based on the trends observed. Prime objective being to highlight the implications of the use of plate or geogrid elements to simulate soil nails, similar geometry and same in-situ soil conditions have been used throughout the analysis.

Both the walls are simulated using PLAXIS 2D following the procedure and preliminary suggestions stated earlier. Two series of simulations 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. At each construction stage of both the walls, 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).

Figure 2 shows the PLAXIS 2D models for both 10 m and 18 m high soil nail walls. Various material properties and other parameters used for simulation are as indicated in Table 2. "P" and "G" in the plots of the analysis correspond to the observations made for simulations using plate and geogrid structural elements respectively.

Figure 3 shows the trend of variation of global factor of safety of the soil nail walls with construction stage. It is evident from Figure 3 that for fully constructed soil nail walls (i.e. 100% construction), consideration of bending stiffness of nails in the analysis have negligible influence on the global stability. In other words, both plate and geogrid structural elements are able to capture similar response and hence, either of the two can be used. However, it is worth noting from Figure 3 that consideration of bending stiffness of nails in the analysis has significant influence during the construction stage. Geogrid elements results in significantly less factors of safety for global stability in comparison to the plate elements. Alternatively, it can be interpreted that bending stiffness plays important role in the stability of soil nail walls during the construction stage. This aspect is overlooked if geogrid elements are used to simulate soil nail in the finite element analysis of soil nail walls.

Figure 4 shows the trend of maximum lateral displacements of the soil nail walls with construction stage. It is evident from Figure 4 that displacement response captured by both geogrid elements and plate elements closely resembles and hence, results in negligible influence on the analysis of soil nail walls.

Figure 5 shows the development of maximum axial force in nails with construction stage. From Figure 5, it can be observed that on an 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 force developed in nails simulated using plate elements is credited to the contribution of bending stiffness of the nails.

This observation is in good agreement with the literature. Figure 6 shows the variation of axial force along the nail length for nails at different levels in 10 m high soil nail wall. Very close resemblance among the axial forces variation along nail length is evident from Figure 6 for the nails simulated using geogrid and plate elements. Similar observations were made for 18 m high soil nail wall.

Development of maximum bending moment and maximum shear force in nails with construction stages are shown in Figures 7 and 8 respectively. It is evident from Figures 7 and 8 that bending and shear capacities of soil nail start mobilising with increasing construction stages. For soil nail walls of greater heights such as 18 m, the magnitude of maximum bending moment and maximum shear force developed in soil nails with construction stages are considerable.

Figure 9 shows the variation of bending moments and shear forces along the nail length for nails at different levels in 10 m high soil nail wall. Similar observations were made for 18 m high soil nail wall. It is interesting to note 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. As mentioned previously, in practice, soil nail are rigidly connected with the facing (FHWA 2003; Joshi 2003) and therefore, it may be desirable to appraise the facing design. Improper design may lead to the bending and/or shear failures of soil nails at or near the facing. Use of geogrid elements for simulating soil nails may lead to the complete negligence of this aspect of the soil nail wall analysis.

Thus, from the above discussions it is apparent that the use of plate elements provides better insight into the analysis of soil nail walls using finite element simulations. Hence, when PLAXIS 2D is used to investigate the cause of failure or to assess the performance of soil nail structure, it is advisable that use of plate structural elements shall be preferred over geogrid structural element for simulating soil nails.

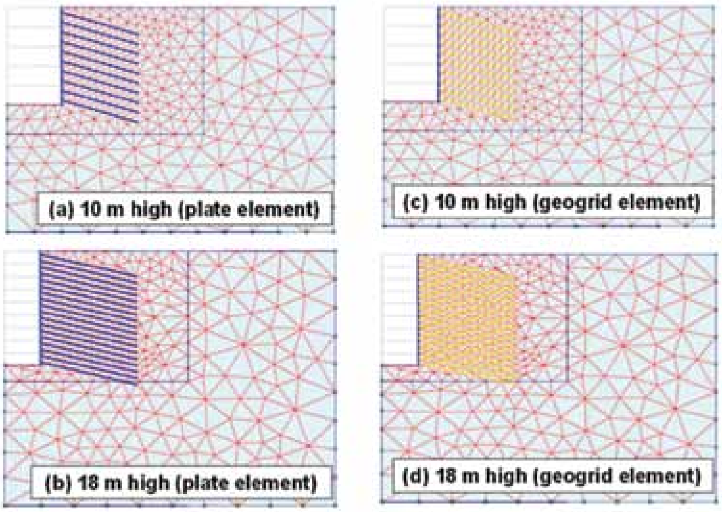

Figure 2: Simulated soil nail walls using PLAXIS 2D

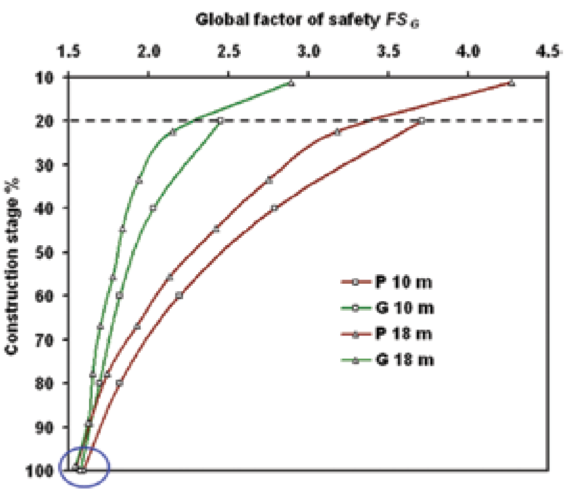

Figure 3: Trend of global factor of safety with construction stage

Influence of mesh density on the soil nail structures simulations

Another important aspect of the numerical simulation of any structure is the density of finite element mesh adopted for the analysis. PLAXIS 2D provides option to the users to select mesh density in the range from very coarse to very fine. Influence of mesh density on the analysis of the soil nail wall and the results corresponding to the analysis of 10m high soil nail wall are presented in Table 3. 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 displacement varied from 20.93mm for very coarse mesh to 28.35mm 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 (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 can be used.

Concluding remarks

In this article, an attempt has been made to bring out implications of the use of plate and geogrid structural elements for simulating soil nails on the analysis of soil nail structures using PLAXIS 2D. Based on the observations from the analyses, use of plate structural elements in comparison to geogrid structural element is advised to simulate soil nails. Further, influence of mesh density on the analysis of soil nail structures is highlighted. Preliminary suggestions made regarding numerical simulations of the soil nail structures that may be useful for the Plaxis user community in general and soil nailing practitioners in particular.

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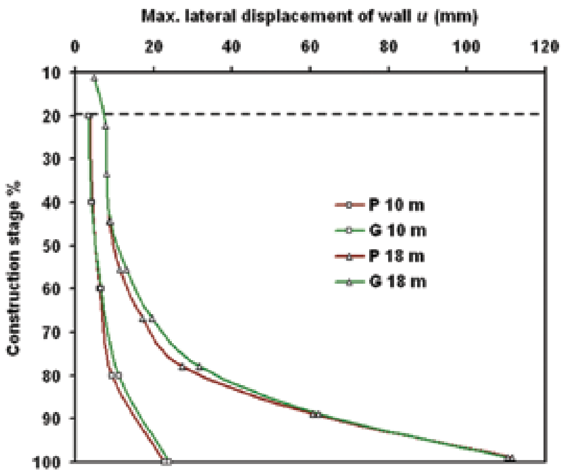

Figure 4: Trend of lateral displacements with construction stage

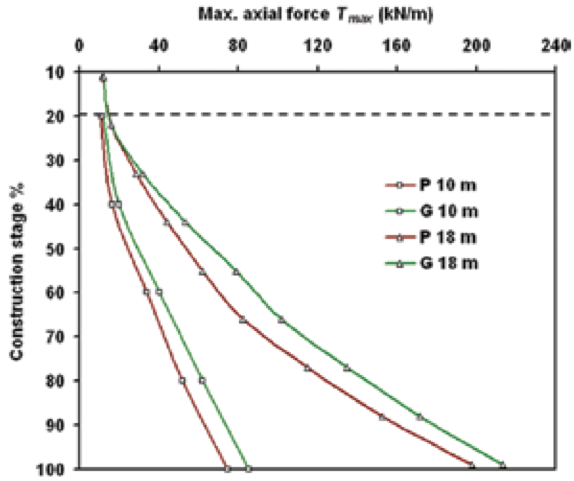

Figure 5: Development of maximum axial force with construction stage

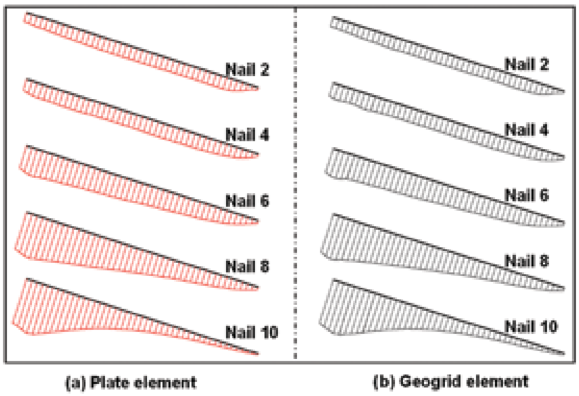

Figure 6: Variation of axial force along nail length (10 m high soil nail wall)

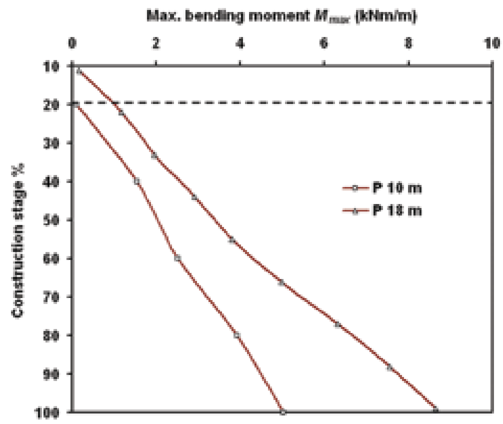

Figure 7: Development of maximum bending moment with construction stage

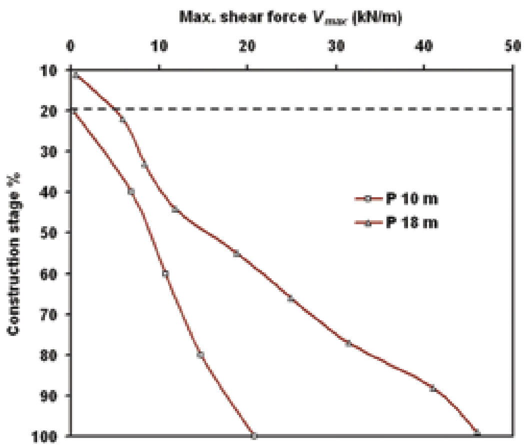

Figure 8: Development of maximum shear force with construction stage

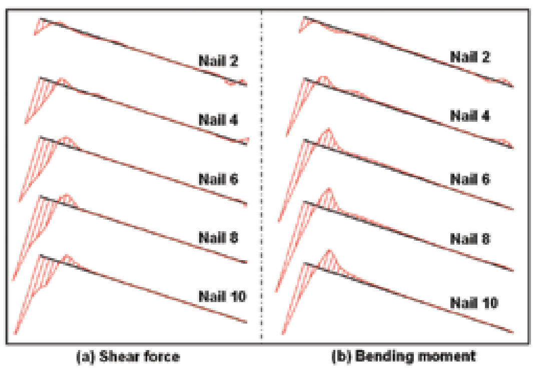

Figure 9: Variation of shear force and bending moment along nail length (10 m high soil nail wall)

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Mesh density	Elements per unit volume	Global factor of safety	Max. lateral displacement (mm)	Total calculation time (min)
Very coarse	0.39	1.610	20.93	1.13
Coarse	0.60	1.598	22.31	1.51
Medium	0.98	1.592	22.86	2.45
Fine	2.08	1.553	24.79	5.51
Very fine	4.14	1.521	28.35	15.15

Table 3: Influence of mesh density on finite element simulation

Note: (1.) FS values correspond to the fully constructed wall. (2.) If FS is to be determined after each construction stage, calculation time may increase even more drastically.