Numerical modelling of soil nailing combined with flexible facing for slope stabilization

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ABSTRACT: Soil nailing combined with a flexible facing made from steel wire meshes is a commonly used and economically efficient structural system for slope stabilization. The overall stability of an unstable slope will be provide by the flexible slope stabilization system. The paper presents a first numerical study on an over-steepened slope. The numerical system and the basic modelling approaches are described. By using a 3D-numerical model the relevance of the shear strength of the soil on the deformation and load bearing behavior is investigated. The deformation of the whole slope stabilization system increases strongly by decreasing cohesion. Current designing approaches does not predict the deformation and calculates an ultimate limit state of the slope stabilization. In consequence, no analytical approach to verify the serviceability of such a system exists. The numerical studies which were conducted in this publication are a first step in a current research project to verify and improve the analytical calculation approaches.

Keywords: slope stabilization; soil nailing; flexible facing; numerical modelling

1. Introduction

Soil nailing combined with a flexible facing made from steel wire meshes is a commonly used and economically efficient structural system for slope stabilization. Soil nails reinforces the natural soil, which strongly decreases earthwork compared to other retaining and supporting systems. The anchored steel wire mesh ensures the transmission of force and guarantees the safety against local and global slope failure.

The geotechnical basics of slope failure and other slope stabilizations are not explained in detail in this publication and can be found in literature, e.g. [1–3].

Soil nailing combined with flexible facing for slope stabilization mainly consists of soil nails, steel wire mesh, connection clips, steel spike plates and supporting ropes, which are usually installed at the boundaries of the slope. The nail spacing for slope stabilization with flexible facing is relatively small. Due to the pretension with a small force and the arrangement of the soil nails in low points, the steel wire mesh fits tightly on the slope surface and small deformations already activate the system.

Different analytical designing approaches of the flexible slope stabilization systems exists in literature for the calculation of local slope failure. An often used calculation approach in Germany is the RUVOLUM design approach [4]. The RUVOLUM design approach investigates superficial instabilities parallel to the slope and between the individual nails. Using this ultimate limit states, the design of the slope stabilization system is conducted. Additionally to the local failure, the global slope stability has to be checked and verified.

Slope stabilization systems are classified in active and passive systems. The active system directly stabilizes the slope and prevents slope failure. A passive slope stabilization system needs to be activated. This is the case, when soil and slope have reached a limit state. Because of that ultimate limit state, high deformation appears in passive systems.

Because only small deformations are needed to activate the system, soil nailing combined with flexible facing for slope stabilization is generally classified as an active system (e.g. [4, 5]).

However, [6] did field measurements of anchored flexible systems for slope stabilization and proved a passive behavior. As a result, [6] concluded that current design methods of these systems should be modified, because most of them assume an active system [7].

Furthermore, [7] reviewed and analyzed different hypotheses assumed in the calculation methods for soil nailing combined with flexible facing for slope stabilization. The analytical calculation approaches are based on the assumption of limit equilibrium and thus no serviceability limit state design exists.

However, the right calculation approach for soil nailing combined with flexible facing is a basic requirement for an accurate dimensioning of the slope stabilization. This is also important from an economic point of view as the cost efficiency of the slope stabilization strongly depends on a well-known deformation and load bearing behavior of the system. Especially the necessary and calculated nail spacing affects the overall number of soil nails and thereby the construction time as well as the construction cost.

Therefore, the current research project deals with the load and bearing behavior of anchored flexible facings for slope stabilization with the aim of an improved calculation approach for the ultimate limit state as well as for the serviceability of the system.

This paper shows first results of numerical simulations of a slope stabilization with soil nailing combined with flexible facing (high tensile steel wire mesh). The results of this numerical simulations as well as the results of further numerical study should be used for a further development and optimization of current designing methods.

2. Numerical modelling

The numerical simulations were calculated with the Finite-Element-Method (FEM) using the software PLAXIS 3D. The basics of FEM are described in [8].

2.1. Geometry and basics of the numerical model and simulation

Fig. 1 shows the geometry and the discretization of the three-dimensional numerical model. The numerical model consists of around 60,000 10-noded tetrahedral elements. The 10-noded tetrahedral elements have four Gaussian integration points and provide a second-order interpolation of displacement [9].The element size near the edges, where no or nearly no deformation will appear, was chosen comparatively large. In the influence area of the slope and the flexible facing the mesh discretization was refined.

The slope angle is 45°. Clay is chosen as soil type for the numerical calculation. The geometry and boundary conditions of the numerical simulation follow often used slope stabilization systems, e.g. [10]. The nail spacing is 2 m x 2 m with an offset from row to row by half the horizontal distance between them. The nail-soil interaction and deformation of the nails were not simulated. The nails are assumed to be fixed and are simulated as a fixed surface with the dimension of a steel spike plate P66 of the Geobrugg AG [11].

The steel wire mesh is simulated as a shell- respectively membrane-element with no bending-stiffness. The steel wire mesh is loaded perpendicularly to their plane by deformation of the over-steepened slope. Due to this loading type, in combination with the low bending stiffness of the flexible facing, the steel wire mesh is loaded mainly by second order geometric effects (geometric nonlinearity). Therefore the geometry of the mesh has to be updated during the stepwise incremental loading. In order to take this second order geometric effects into account, the simulations were done with the application of an updated Lagrange-formulation. This leads to more realistic steel wire forces and thus to a more realistic load bearing and deformation behavior of the whole system.

Ideal contact between the materials was assumed (no interface elements).

Fig. 2 shows the cross-section which was used for the analysis of the load bearing and deformation behavior.

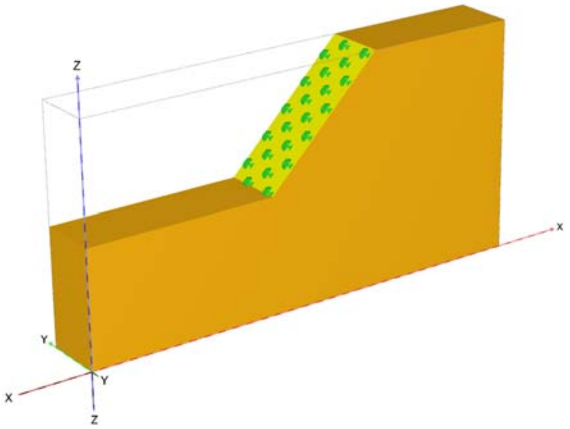

Figure 1. Three-dimensional numerical model.

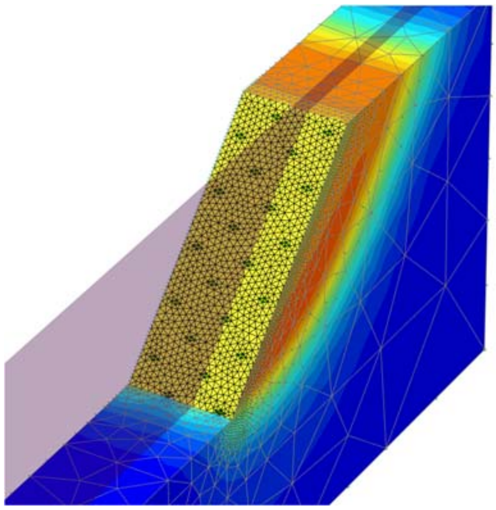
Figure 2. Cross-section 1 for the analysis of the load bearing and deformation behavior

2.2. Material parameters used in the numerical simulation

The soil behavior is simulated by using the Hardening Soil model of [12, 13] with small strain stiffness extension of [14] (HS small). Using the HS small model as a constitutive law, the non-linear soil behavior is taken into account and thus realistic load bearing and deformation behavior of the whole system can be calculated and predicted. Table 1 shows the used material parameters of the soil for the HS small model. The varying parameter of the numerical simulations was the cohesion of the clay. The cohesion in the numerical model was 5 kN/m², 10 kN/m² and 15 kN/m², which is a realistic range for clay. The other soil parameters are constant.

The steel wire mesh (flexible facing) is modeled as a linear-elastic element. The mesh is modelled with an anisotropic axial stiffness of 350 kN/m in cross direction and 2950 kN/m in longitudinal direction. The mesh has no bending stiffness. The used anisotropic axial stiffness represents a widely distributed and often used steel wire mesh for flexible slope stabilization systems of over-steepened slopes.

Table 1. Soil material parameters used in the numerical simulations

Parameter	Unit	Clay
γ_{unsat}	kN/m³	18
E_{50}^{ref}	kN/m²	$8 \cdot 10^3$
E_{oed}^{ref}	kN/m²	$8 \cdot 10^3$
E_{ur}^{ref}	kN/m²	$20 \cdot 10^3$
power (m)	-	0,9
c_{ref}	kN/m²	5/10/15
φ	°	25
ψ	°	0
$\gamma_{0.7}$	-	$3 \cdot 10^{-4}$
G_0^{ref}	kN/m²	$25 \cdot 10^3$
ν_{ur}	-	0,2

2.3. Simulation process

After generating the initial stress state of the soil (K0-Procedure) of the numerical simulation, the steel wire mesh and the fixities which simulate the soil nails were activated (wished in place). The standard fixities were used (z_{min} fixed in all directions, x and y fixed horizontally). Afterwards the soil weight and the gravity were activated.

3. Results and discussion

A comparative numerical calculation without a flexible slope stabilization system was conducted. As expected, the over-steepend slope with an slope angle of 45° is not stable without an extra stabilization. By plotting the shear strains in the last step, Fig.3 shows the ultimate limit state of the system. Fig. 4 shows qualitatively the total displacement of the numerical simulation (no legend) without a slope stabilization system. The shear strains show the well-known shape of the slope failure surface from analytical slope stability analysis, e.g. after [15, 16], which was calculated analytically and is shown in Fig. 5.

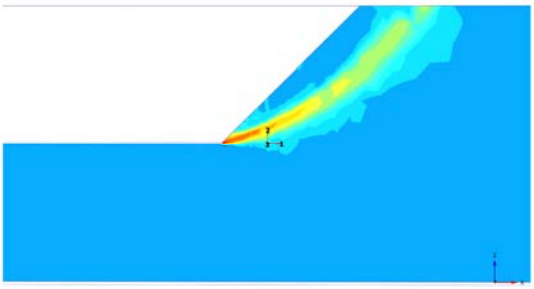

Figure 3. Shear strains of an over-steepened slope without slope stabilization system, ultimate limit state reached: slope failure.

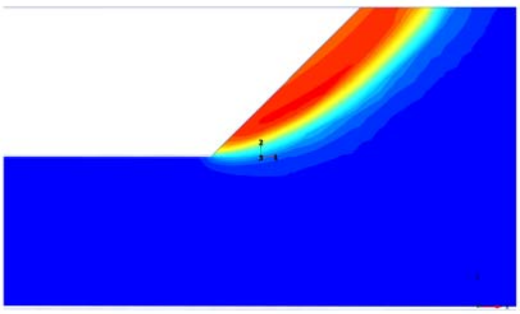

Figure 4. Shape of total displacement of an over-steepened slope without slope stabilization system; ultimate limit state reached: slope failure.

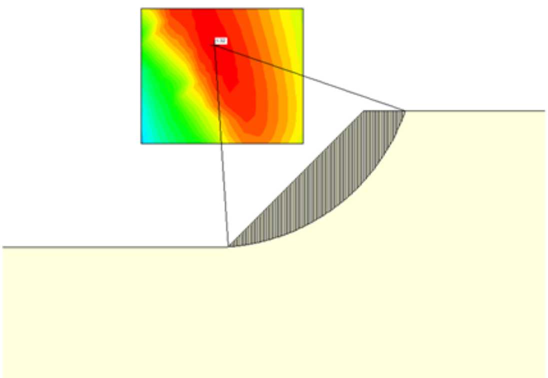

Figure 5. Analytical slope stability analysis after BISHOP [15, 16].

Fig. 6 to Fig. 10 show the results of the numerical simulation of the slope stabilization with soils nails and a flexible facing (high tensile steel wire mesh).

First of all, it can be observed that the deformation and load bearing behavior are realistic and generally, the qualitative progression of deformation is as expected. The simulated high tensile steel wire mesh is supported and fixed at the simulated nails and steel spike plates. Between the supporting points the soil body moves and the mesh deforms like a catenary (Fig. 6 and Fig. 7). Hence, the slope stabilization system can be modelled and calculated with the finite element method and a parametric study can be conducted to determine the influence of different parameters. This paper shows the influence of the effective cohesion on the deformation and load bearing behavior of the slope stabilization system.

Fig. 6 shows the total displacements of the steel wire mesh respectively the slope surface in cross-section 1 after Fig. 2 by varied cohesion of the modelled clay. The x-axis shows the distance from slope foot in m (length) and the y-axis the total deformation in cm. The total deformation means that the plotted deformation is not in a fix direction and is calculated by the square root of the sum of the square of the three directions. The points with no deformation shows the position of the soil nails which are simulated as a fixed surface. Consequently, soil nail interaction is simplified not simulated. Because of this simplification, a direct shear force from the nail as assumed for superficial instabilities parallel to the slope in RUVOLUM dimensioning method of the nails is not simulated. However, this simplifies the numerical model significantly and the influencing parameter of soil nail interaction (skin friction) is neglected. As a result, a clear correlation between the cohesion and the deformation as well as the load bearing behavior of the flexible facing can be observed without an extra parameter like the soil nail interaction.

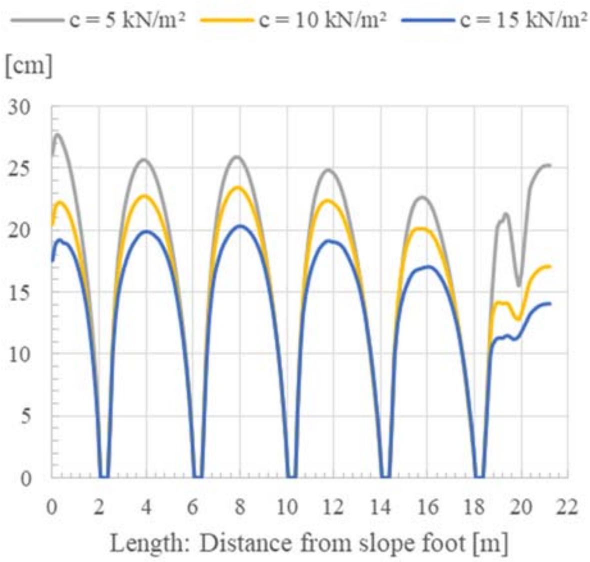

Figure 6. Total displacements of the steel wire mesh respectively the slope surface in cross-section

With decreasing cohesion of the soil (clay), the deformation of the whole system increases (Fig. 6 and Fig. 8). The maximum deformation in the numerical simulation with a cohesion of 5 kN/m² is around 20 cm near the foot of the slope. This high deformation exceeds probably the limit value from the designer and thus the serviceability of the system although the ultimate limit state is not reached due to the slope stabilization system. Nevertheless, the current design approaches are not able to estimate the deformation of the system. Hence, the deformation is not taken into account when designing a stabilization system for an unstable slope. The maximum deformation with a cohesion of 10 kN/m² is around 23 cm and with a cohesion of 15 kN/m² around 20 cm. The increase of deformation from cohesion of 15 kN/m² to 5 kN/m² is around 40 %.

Fig. 8 shows the surface deformation of the numerical simulation with cohesion of 5 kN/m² (a) and a cohesion of 15 kN/m² (b). The qualitative deformation and load bearing behavior is comparable.

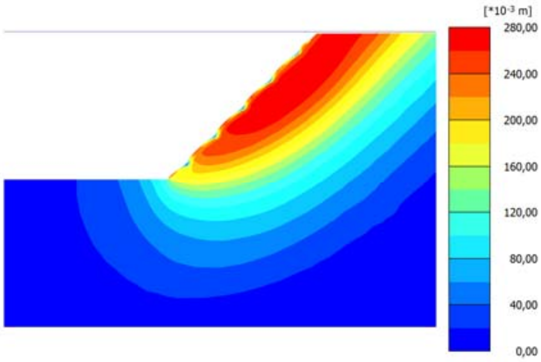

Figure 7. Total displacement of the numerical simulations of the slope stabilization system with a cohesion of 5 kN/m² in cross-section 1.

Fig. 9 shows the shear strains (total deviatoric strain) in cross section 1. Comparatively small deviatoric strains can be identified nearly along the slope failure. Due to the slope stabilization, a slope failure is avoided. The main shear strains occur parallel to the slope. The shear strains correlate to the analytical calculation approaches, e.g. the Ruvolum dimensioning method. The local instability parallel to the slope is verified.

a) 5 kN/m² b) 15 kN/m²

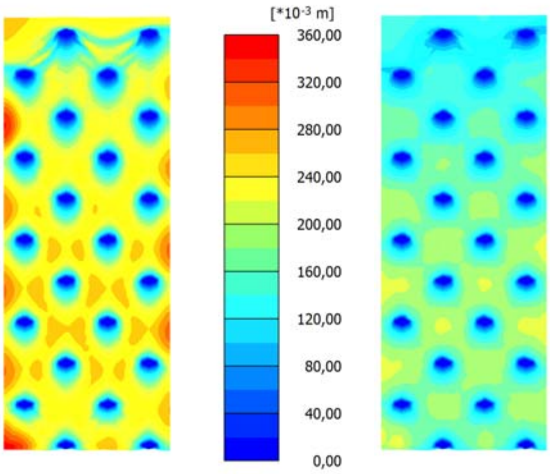

Figure 8. Surface deformation of the numerical simulations with a cohesion of 5 kN/m² (a) and a cohesion of 15 kN/m² (b).

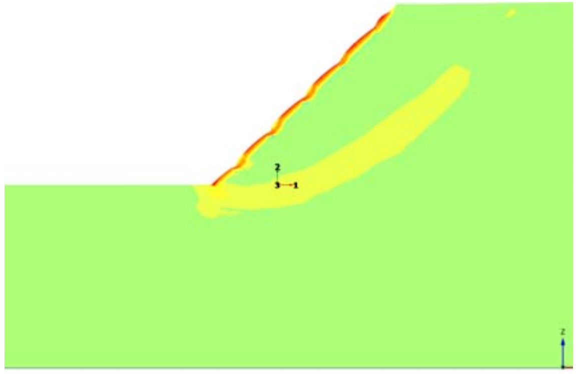

Figure 9. Incremental shear strains of the numerical simulations of the slope stabilization system with a cohesion of 5 kN/m² in cross-section 1.

Fig. 10 and Fig. 11 shows the axial forces of the steel wire mesh in cross-section 1. Fig. 10 shows the forces in longitudinal direction and Fig. 11 the axial forces in cross direction. The maximum normal forces of the steel wire mesh are directly underneath the soil nails. The forces at the foot of the slope are slightly higher than at the top of the slope, which is consistent with the deformation of the slope. The progression of the normal forces decreases starting from the maximum value and has another peak directly above the next nail (lower than the maximum value). One conspicuous difference is that the maximum value directly under a soil nail is nearly the same in all variations of the cohesion and the forces above the soil nails differ clearly. The forces above the soil nails in the numerical simulation with a cohesion of 5 kN/m² are around two to three times higher than the simulation with a cohesion of 15 kN/m².

4. Conclusion and outlook

The right calculation approach for soil nailing combined with flexible facing is a basic requirement for an accurate dimensioning of the slope stabilization.

The numerical investigations led to the following results:

- The numerical simulations of soil stabilization with anchored flexible facing showed a realistic deformation and load bearing behavior.
- With decreasing cohesion of the soil, the deformation of the whole system increases.
- The current design approaches consider limit equilibrium. The numerical simulations showed that large deformation of the slope depending on the soil conditions and material parameters can occur althoug the ultimate limit state is not reached. These large displacements are potentially not acceptable. However, a proof of serviceability does not exists.
- Althoug the maximum deformation is much higher for a lower cohesion, the maximum normal forces of the steel wire mesh were nearly the same in the different numerical simulations.

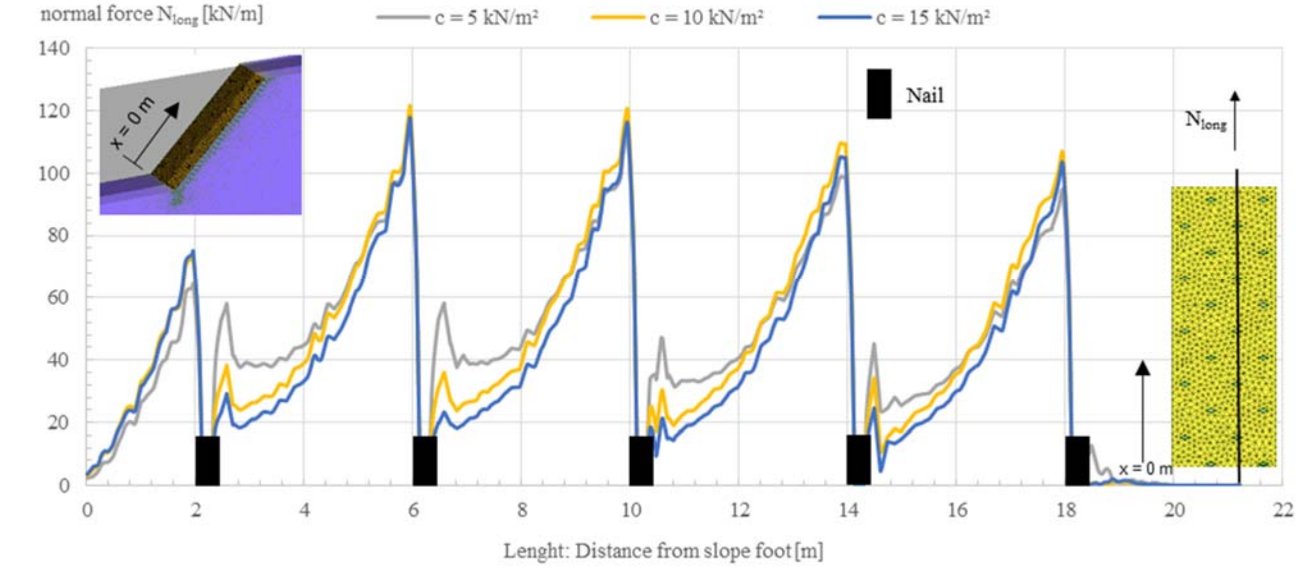

Figure 10. Axial forces in longitudinal direction of the steel wire mesh (cross-section 1)

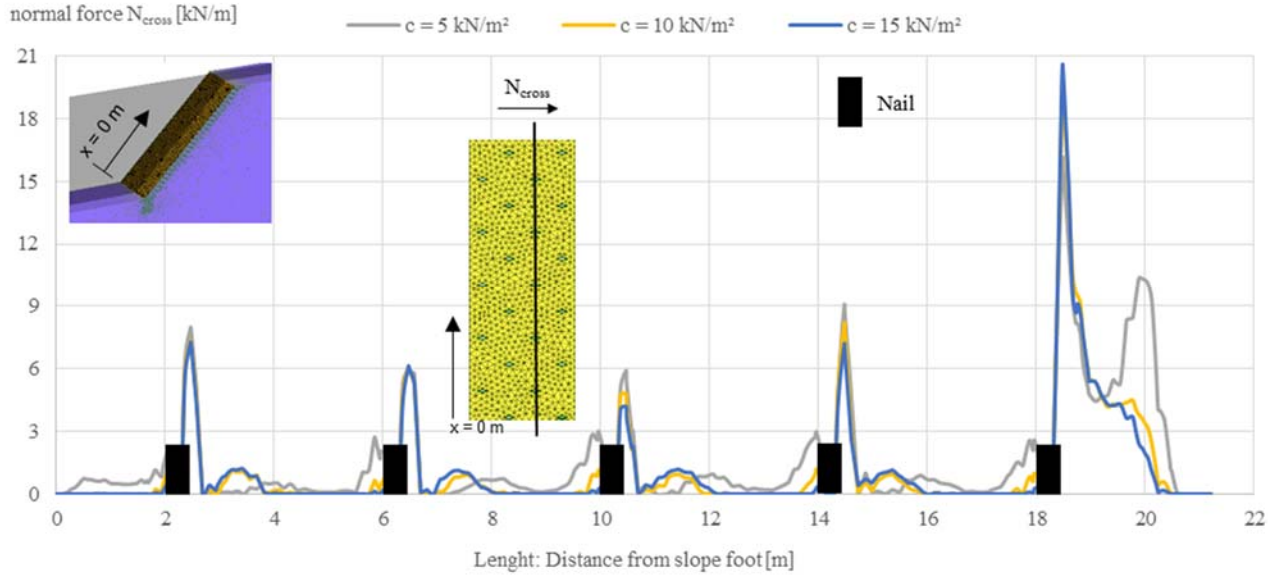

Figure 11. Axial forces in cross direction of the steel wire mesh (cross-section 1)

As an outlook and target for additional investigations on soil nailing combined with flexible facing for slope stabilization, following points should be mentioned:

- A verification of the numerical model using experimental data of large scale field tests will be carried out.
- Further studies on the influence of the shear strength parameters of cohesive and non-cohesive soils will be conducted.
- The influence of the nail arrangement as well as the nail soil interaction on the load bearing and deformations behavior will be investigated.
- The influence of the axial stiffness (isotropic as well as anisotropic) of the steel wire mesh will be examined.

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