Investigations on load-bearing behavior 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. Soil nails reinforce the natural soil, which strongly decreases earthwork compared to other retaining and supporting systems. The steel wire mesh ensures the transmission of force and guarantees the safety against local and global slope failure. In a first step the paper describes the structural system of soil nailing combined with flexible facing. For instabilities near the surface (local instabilities) state of the art calculations are outlined. To verify and improve the existing designing approaches, full scale in situ tests were conducted. Among others, different flexible facing systems, nail arrangements, and soil conditions were investigated. The flexible slope stabilization system and the soil were installed in a large box with a dimension of 12 m x 10 m. After the installation, the test box was lifted up stepwise using a crane. Different parameters like three dimensional deformation, rope forces, as well as the moment and normal forces in the nails were measured. The test results are used for numerical back analysis with a three dimensional finite element method. Using the validated and calibrated numerical model, extended parametric studies by 2-dimensional and 3-dimensional non-linear finite element analyses will be conducted in the future to identify the main influencing parameters.

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 reinforce 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 can be found in literature, e.g. [1–5].

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 edge 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 already small deformations can activate the system.

For the calculation of local slope failure different analytical designing approaches of the flexible slope stabilization systems exist in literature. [6] reviewed and analyzed different hypotheses, that are assumed calculation methods for soil nailing combined with flexible facing for slope stabilization. They concluded that analytical calculation approaches are based on the assumption of limit equilibrium. 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 calculated nail pattern affects the overall number of soil nails and thereby the construction time as well as the construction cost.

An often used calculation approach in Germany and Switzerland, as well as for projects worldwide, is the RUVOLUM design approach [7]. 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. In addition to local failure, global slope stability has to be checked and verified. The RUVOLUM design approach is based on a force-balance approach as well as the Mohr-Coulomb failure criterion for the ultimate limit state.

In order to improve the understanding of deformation and load-bearing behavior of anchored flexible facing for slope stabilization systems, a research project was initiated. Large scale field tests were conducted. Results of the large-scale field tests were shown, e.g. in [8–10]. The large-scale field tests will be simulated with a 3-dimensional non-linear finite element model. Based on the results and measurement data, the numerical simulation model and the modelling approaches will be examined. The validated and verified numerical model will be used for a parametric study.

This paper shows the numerical back analysis of one large-scale field test. The deformation behavior from the field test and the numerical simulation are compared. If the deformation and load-bearing behavior can be simulated realistically, the numerical model can be used for numerical parametric studies. This could help to develop and optimize current designing methods.

2. Large-scale field tests
Overall, 31 large-scale field tests were conducted to improve the knowledge of deformation and load-bearing behavior of a slope stabilization system. One main aim of the large-scale tests was a validation and verification of the design approach. Different parameters were varied to analyze their influence in large-scale.

The inclinable large test box had dimensions of 12 m x 10 m x 1.2 m. The test box was lifted up on one site by using a crane to simulate different slope angles. While lifting up the test box and increasing the slope angle, the surface deformation was measured by using a laser scanner. The test box was lifted up in 5-degree steps.

The soil volume, the compaction method, and the nail type were the same in all large-scale field tests. Other influencing parameters were modified systematically to determine their influence. Two different soil types were chosen for the large-scale tests to investigate the influence of the shear strength. Furthermore, the steel wire mesh, the steel nail plates (spike plates), and the nail pattern were changed during the testing period.

In the numerical back analysis, the large-scale field test no. 29 was simulated. The test was conducted with the high tensile steel wire mesh TECCO G65/3 and P33 spike plates. Silty gravel was used as test soil and nail spacing of 3.5 m x 3.5 m was chosen.

The test box inclination was measured manually (manual goniometer) and electronically (inclination sensor). Three earth pressure cells were installed (bottom of the box, under the mesh and in the middle of the soil layer). Load cells at the upper and lower boundary ropes measured the forces during the large-scale test. Strain gauges were installed on four nails to measure bending moments and normal forces.

The first laser scan was taken while the test box was still horizontally. The laser scans, which were taken during the test, are compared to the first scan to get the surface deformation. After the first inclination of 30 degrees the test box was lifted up stepwise in 5-degree steps. At an inclination of around 40 degrees the first small deformation occurred. At the same inclination, the first significant changes in earth pressure, rope forces, and nail forces occurred. At an inclination of around 48 degrees larger deformation could be recognized visually, which is verified by the result of the laser scan at an inclination of the test box of 50 degrees.
Figure 1 shows photos of the test box during test no. 29. At the test box inclination of 45 degrees no major deformation is visible. Surficial soil failure can be identified at an inclination of 50 degrees. Figure 2 shows the results of the laser scanning. The deformation increased from around 20 cm to 40 cm at the bottom of the test box. The soil at the top of the box slid parallel to the box. Due to this complete moving of the soil, large deformation appeared. The test was continued up to an inclination of the test box of about 77 degrees. At this inclination the mesh broke. The rupture appeared at the center nail in the middle row.

![Test box inclination 45°](image1)

![Test box inclination 50°](image2)

**Figure 1.** Test setup of test no. 29 at the inclination of 45° (a) and 50° (b).

![Test box inclination 45°](image3)

![Test box inclination 50°](image4)

**Figure 2.** Results of the laser scanning; surface deformation [m] of test no. 29 at the inclination of 45° (a) and 50° (b).

### 3. Numerical Analysis

The numerical simulations were calculated with the Finite-Element-Method (FEM) using the software PLAXIS 3D. The basics of FEM are described in [11].
3.1. Geometry and basics of the numerical model and simulation

Figure 3 shows the geometry and the discretization of the three-dimensional numerical model for the numerical back analysis of the large-scale field test. The numerical model consists of around 25,000 10-noded tetrahedral elements. The 10-noded tetrahedral elements have four Gaussian integration points and provide a second-order interpolation of displacement [12].

The inclination angle of the test box was simulated stepwise from 30 degree to 60 degree. The geometry and boundary conditions of the numerical simulation follow the large-scale field test. The nail spacing is 3.5 m x 3.5 m with an offset between rows by half the horizontal distance. 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 P33 from Geobrugg AG. The steel wire mesh is simulated as a shell- respectively membrane-element with no bending-stiffness. It is loaded perpendicularly to their plane by deformation of the soil. 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 behaviour of the whole system.

An auxiliary soil layer and an interface element was used to enable a relative deformation between the test box and the soil. Figure 3 shows the numerical model at an inclination of 45° of the test box. The whole simulation model and boundary conditions are activated in one phase (wished in place). The stepwise uplift of the test box was not simulated directly.

Figure 3. Three-dimensional numerical model of the large-scale field test no. 29.

3.2. Material parameters used in the numerical simulation

The soil behavior is simulated by using the Hardening Soil model of [13, 14]. Using the Hardening Soil 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. Table 1 shows the applied material parameters of the soil for the Hardening Soil model. The shear parameters of the soil were determined with laboratory tests [15]. The stiffness of the soil represents empirical values.
The steel wire mesh (flexible facing) is modelled as a linear-elastic element. The mesh is modelled with an anisotropic axial stiffness of 300 kN/m in cross direction and 2,700 kN/m in longitudinal direction. The mesh has no bending stiffness.

**Table 1.** Soil material parameters applied in the numerical simulations

| Parameter   | Unit       | silty gravel |
|-------------|------------|--------------|
| $\gamma_{\text{unsat}}$ | kN/m$^3$  | 18           |
| $E_{50}^{\text{ref}}$ | kN/m$^2$  | $3 \cdot 10^3$ |
| $E_{\text{oed}}^{\text{ref}}$ | kN/m$^2$  | $3 \cdot 10^3$ |
| $E_{\text{ur}}^{\text{ref}}$ | kN/m$^2$  | $75 \cdot 10^3$ |
| power (m)   | -          | 0.6          |
| $c_{\text{ref}}$ | kN/m$^2$  | 0.1          |
| $\phi$      | °          | 38           |
| $\psi$      | °          | 8            |
| $\nu_{\text{ur}}$ | -         | 0.2          |

4. Results

Figure 4 shows the surface deformation of the field test no. 29 and the calculated deformation in the numerical back analysis. Almost no deformation was calculated for an inclination of the test box of 30 degrees because the inclination is much lower than the maximum shear strength of the soil. The deformation in the large-scale field test is also extremely low. The deformation in the large-scale field test and the calculated deformation fit quite well up until an inclination of the test box of 45 degrees.

The strong increase in deformation at an inclination of 50° of the test box is a result of a big soil slide appearing in the field test (figures 1 and 2). The soil at the top of the test box moved downwards. Also this soil failure provoked high deformation of the nail heads, which were analyzed at seven points. Table 2 shows the deformations of the nail heads at an inclination of 60 degrees.

The strong increase of deformation from 45 degrees to 50 degrees is not simulated in the numerical model. But the gradient of the curves from an inclination of 50 degrees to 60 degrees is comparable. Some assumptions of the model might explain the difference and the offset between the results of the field test and the numerical simulation.

First, the nails are modeled in a simplified way with a fixed nail plate at the nail heads. This simplification leads to lower deformation in the numerical simulation. Secondly, deformations strongly increase with increasing inclination and the effect of a slip between soil and test box as well as between soil and mesh is getting higher with increasing inclination. Relative displacement of this size between test box and soil cannot be simulated with FEM. The numerical simulation of this slip is limited because the Finite-Element-Method is a mesh-based method. The interaction between soil and test box is simulated by using an interface element and hence only a small relative displacement can occur. The steel wire mesh and the soil had full contact in the numerical simulations. The influence of an interface element between the mesh and soil will be investigated in further studies. Nevertheless, the main deformation and load bearing behavior can be simulated. The gradient of the deformation curves is still comparable after 50 degrees.

Figure 5 shows the surface deformation of the large-scale field test (a, c) and the numerical simulation (b, d) for an inclination of 45 degrees (a, b) and 60 degrees (c, d) of the test box. The surface
deformations of the field test and the numerical simulation show qualitatively strong similarities. Hence, a correct and realistic load-bearing behavior in the numerical simulation can be assumed.

**Figure 4.** Comparison of surface deformation of large-scale field test no. 29 and the numerical back analysis with a three-dimensional finite element model.

**Figure 5.** Surface deformation of the large scale field test (a, c) and the numerical simulation (b, d) of test no. 29 at the inclination of 45° (a, b) and 60° (c, d); all plots have different scaling.
Table 2. Displacement of the nail heads in the large-scale field test no. 29 at an inclination of the test box of 60°.

| nail number | x [mm] | y [mm] | z [mm] |
|-------------|--------|--------|--------|
| 1           | -151   | 6      | -23    |
| 2           | -423   | 10     | -72    |
| 3           | -392   | 2      | -59    |
| 4           | -144   | 6      | -27    |
| 5           | -305   | -4     | -31    |
| 6           | -398   | 4      | -51    |
| 7           | -268   | -5     | -26    |

Figure 6. Axial forces of the steel wire mesh in longitudinal direction (a, c) and in cross direction (b, d) of the steel wire mesh in the numerical simulation of test no. 29 at the inclination of the test box of 45° (a, b) and 60° (c, d); all plots have different scaling.
Figure 6 shows the axial forces in longitudinal and in cross direction of the simulated steel wire mesh at an inclination of 45 degrees and 60 degrees of the modelled test box. The maximal normal forces of the steel wire mesh are in longitudinal direction directly underneath the nail heads. The axial force is around 2.5 to 3-times higher at an inclination of 60 degrees compared to 45 degrees. The progression of the axial forces is consistent to the deformation and are qualitatively plausible. Due to the large soil movement at the top of the box, the mesh is hanging like a rope between the upper row of nails. This effect can be seen in the plots of the axial forces of the mesh in cross direction (b, d).

5. Conclusion and outlook
The numerical simulations fit quite well to the large-scale field test. The discrepancy for higher inclination angles can be explained and it can be assumed that the main difference results from the simplification of fixed nail heads and the contact formulation and simulation. The soil-nail interaction will be investigated in further studies. The influence of contact and boundary conditions will be neglected in the planed parametric numerical studies by simulating a sufficient large part of a slope (dimension of the numerical model). Hence, the load-bearing and deformation behavior of soil nailing combined with flexible facing for slope stabilization can be simulated realistically. The numerical model can be used for further parametric studies to investigate the main influencing parameters in practical relevant application. Such parametric studies could lead to a better understanding of the deformation and load bearing behavior of anchored flexible facing and might be used for the verification and optimization of current design approaches like the RUVOLUM design method.

Due to high practical relevance the GTU Ingenieurgesellschaft mbH is doing research in cooperation with the Geobrugg AG and the Budapest University of Technology and Economics on the field of slope stabilization systems. Especially the cost-efficient slope stabilization system with soil nailing and flexible facing is research content. The aim of the research project is an improved and realistic numerical simulation of the slope stabilization system including all relevant parameters. The numerical model will be validated using further experimental data. The validated numerical simulation model will be used for further investigations and numerical parametric studies. The results will be used to find the main influencing parameter and to improve the current design and calculation approaches for ultimate limit state (ULS) as well as for serviceability limit state (SLS).

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

- Parametric studies on the influence of 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 deformation behavior will be investigated.
- The influence of the axial stiffness (isotropic as well as anisotropic) of the steel wire mesh representing different facings and wire diameter will be examined.
- Interaction and relation between the nail forces (axial force and bending moment) and the mesh forces will be investigated.
- Determination and development of the load-bearing system / static system to verify and improve current calculation approaches soil nailing combined with flexible facing.
- Development of a calculation approach for a prediction of the deformation behavior of anchored flexible facings for slope stabilization taking the main relevant system parameter into consideration. This will enable the verification of the serviceability limit state (SLS), which cannot be proofed with current designing methods.

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