Large-scale field tests with flexible slope stabilization systems

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Abstract

In the scope of a research project by the Commission for Technology and Innovation (CTI) of the Swiss Federal Department of Economic Affairs, Education and Research, large-scale field tests with flexible slope stabilization systems were performed in Winterthur, Switzerland under the direction of the Bern University of Applied Sciences in Burgdorf. For this purpose, a 13 x 15 m steel frame was filled with soil material and tilted up to 85° using a 500 to crawler crane. Different mesh and net coverings combined with a nail anchoring system were used to stabilize the soil material against instabilities near the surface. This article gives an overview of the test assembly and summarizes the results from the large-scale field tests performed. In addition, the retrograde calculation of the RUVOLUM dimensioning concept was verified. The large-scale field tests performed create an ideal foundation for a better understanding of the load bearing capacity of flexible slope stabilization systems and comparison of different meshes under same conditions as well for further developing and adapting them to project-specific requirements.

Keywords: Flexible slope stabilization system, High-tensile steel wire, Large-scale field test, RUVOLUM

1. Introduction

A total of 31 large-scale field tests were performed on flexible slope stabilization systems in cooperation with industry partner Geobrugg AG. Varying the distance between nails and the soil materials made it possible to analyze the load bearing capacity of the different systems in detail. This allowed for an objective system comparison at similar conditions.

2. Testing equipment

The testing equipment consists of a 13 x 15 m steel frame which can be filled with soil material through a 10 x 12 m surface up to a layer thickness of 1.20 m. The incline of the frame can vary between 0° and 85° by lifting it with a 500 to crane.

The base and side areas of the test area are covered flat with rough wooden planks. To ensure that the sliding surfaces of instabilities close to the surface form within the filling material and do not follow the board floor, wooden slats with a cross sectional area of 30 x 60 mm were applied to increase roughness in the transverse direction (cf. figure 2).

Figure 1. Total overview of testing equipment

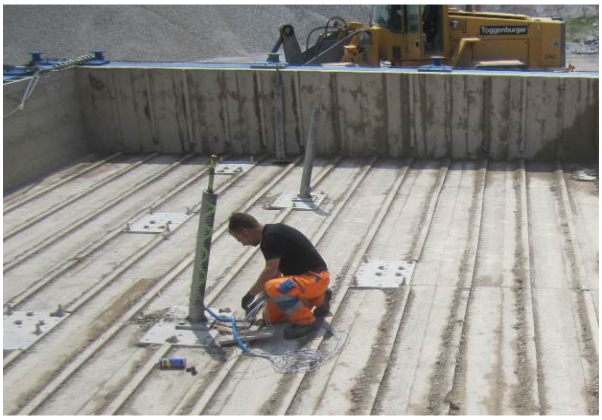

Figure 2. Test no. 13, after dismantling mesh cover and removing material, nail grid 3.5 x 3.5 m.

The mesh cover was sewn to upper and lower support ropes. Depending on the safety system, they exhibit a diameter of 14 - 22 mm and are braced against laterally positioned bollards. To create a cut-out from an infinitely long slope which is as realistic as possible, the mesh cover was screwed to the side of the frame using steel U-profiles. This created a bedding which was immovable in the lateral direction.

GEWI D = 28 mm or D = 32 mm with solidified cladding tubes were used as nails. The connection to the framework construction was made with a base plate welded to the nail which was itself screwed onto another steel plate. The cladding tube was led into a steel tube fastened to the base plate. The nail is considered bend-proof in its connection to the frame. Conventional solidification of the nail was not possible due to reasons concerning the installation and time frame.

Spike plates adjusted to the mesh were used to fasten it. The upper support cable was not held up with nails; instead, it was fastened against bollards using fixing ropes. The lateral distance between the bollards corresponded to the respective horizontal distance between the nails. The mesh webs exhibited widths of 2.0 to 3.5 m and were connected to one another in a force-locking manner via system-specific connectors. To prevent the non-compacted gravel from falling out between the mesh, a geotextile with an opening width of 20 x 20 mm with low tensile strength and no static function was laid out under the mesh cover starting with the 4th test.

3. Goals

The overarching goal for the execution of large-scale field tests was to analyze and better understand the load bearing capacity of this type of slope stabilization system under different limiting conditions and under conditions which are as real as possible. This was done with view to the optimal application of such systems in practice. Only instabilities close to the surface with a maximum thickness of 1.20 m were examined in this research project. The global stability and thereby the dimensioning of the nail anchoring system to prevent fracture mechanisms with deeper sliding surfaces will not be discussed.

4. Soil material

In some tests, round gravel with a grain size of 16 – 32 mm was used as soil material (Figure 3, left). This non-compacted material always fell into the densest bedding during installation. This reflects natural conditions only in a limited manner; however, in view of limiting conditions which are as useful as possible for comparison, this is optimal for test purposes.

In other tests, sandy gravel made of broken-up recycling material with a grain size of 0 - 63 mm was used (Figure 3, right). It has good interlocking properties and is similar to slope scree.

The following table summarizes the specific soil values on characteristic level. These are based on many years of experience and are used for comparative calculations. The friction angle of the non-compacted gravel corresponds with the inclination of the material cone in the immediate vicinity.

Table 1. Specific soil values.

Soil Material	φ'_k [°]	c'_k [kN/m^2]	γ_k [kN/m^3]
Round gravel, 16 – 32 mm	33	0	20
Sandy gravel made of broken-up recycling materials, 0 – 63 mm	38	0	21

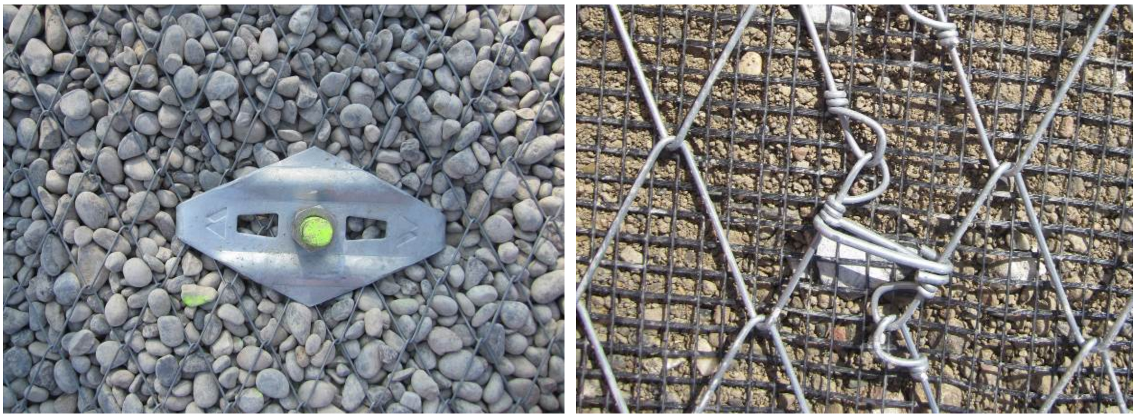

Figure 3. Mesh TECCO® G65/3 and round gravel 16 - 32 mm (left) as well as sandy gravel 0 – 63 mm, with connection clips and geotextile (right) .

5. Measurement equipment

The surface including nail heads and steel frames were scanned at horizontal position using laser scans to serve as a reference level. White cones set on the nails and various mirrors served as orientation aids and reference points. The scan was repeated after changing the inclination by 5° each time. Figure 4 shows a cross-fade of individual scans. A pendulum and an automatic inclinometer are used to determine the inclination of the steel frame.

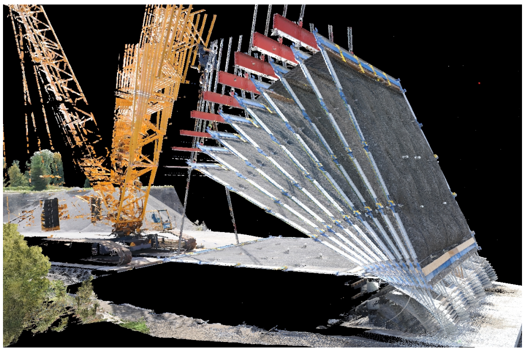

Figure 4. Test no. 4, TECCO® G65/3 + P33, cross-fade of individual scans.

The displacements of the top middle nail were measured via a rope potentiometer to verify the scan data and monitor the deformation during the test. In addition, the forces in the upper and lower support wire ropes were determined using load cells specially adapted to the conditions.

Information on developments in selected nails during changing conditions was gathered using strain gauges. Analyzing this would go beyond the scope of this article. A dissertation will provide a detailed analysis.

6. Test results

In order to analyze the load bearing capacity and de-formation behavior of flexible slope stabilization systems, laser scans at a steel frame inclination of 60° are compared with one another in the following. Figure 5 shows the state of a TECCO® G65/4 type high-tensile steel wire mesh with spike plate P66 (width of 66 cm) with round gravel and a nail grid of 3.5 x 3.5 m. Figure 6 shows the same situation with the same spike plate and nail arrangement as well as the same soil material. The only different is the mesh. Instead of a high-tensile steel wire mesh with a longitudinal tensile strength of at least 250 kN/m and a wire diameter of 4 mm, a high-tensile steel wire mesh with the same mesh size but with a wire diameter of 3 mm and a tensile strength of at least 150 kN/m was used. The stronger mesh is somewhat stiffer under the same conditions. It is subject to less deformation and the soil material slides downwards to a lesser degree.

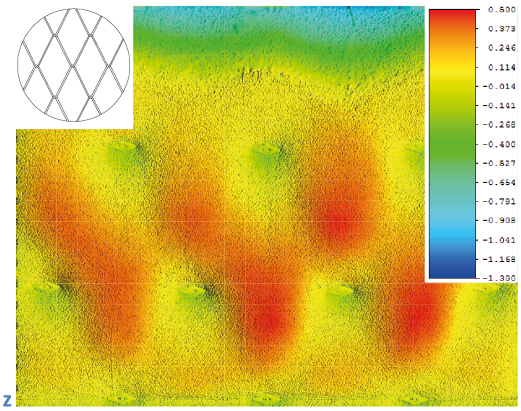

Figure 5. Test no. 12, TECCO® G65/4 + P66, nail grid 3.5 x 3.5 m, round gravel 16 - 32 mm, α = 60°.

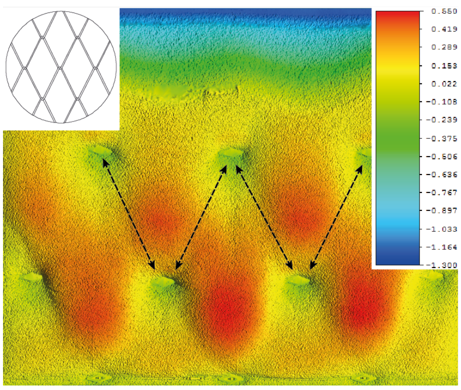

Figure 6. Test no. 14, TECCO® G65/3 + P66, nail grid 3.5 x 3.5 m, round gravel 16 - 32 mm, α = 60°.

If you compare figure 6 with figure 7, the following becomes clear: On the one hand, smaller spike plates are used (33 cm wide spike plate, type P33 instead of 66 cm wide spike plates, type P66). On the other hand, a high-tensile steel wire mesh with a wire diameter of 2 mm and a longitudinal tensile strength of at least 65 kN/m is used. The stabilizing lateral influence of a smaller spike plate is weaker than with a larger one with sufficient bending stiffness. Furthermore, a somewhat weaker mesh under the same limiting conditions is somewhat more stressed, which becomes clear due to somewhat larger deformations with a wider bulge which slides downwards to a larger degree.

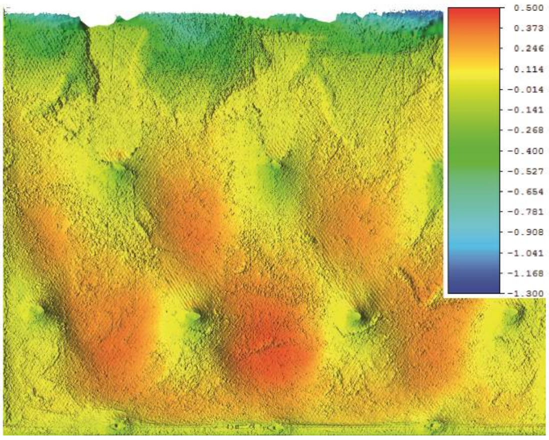

Figure 7. Test no. 17, TECCO® G65/2 + P33, nail grid 3.5 x 3.5 m, round gravel 16/32 mm, α = 60°.

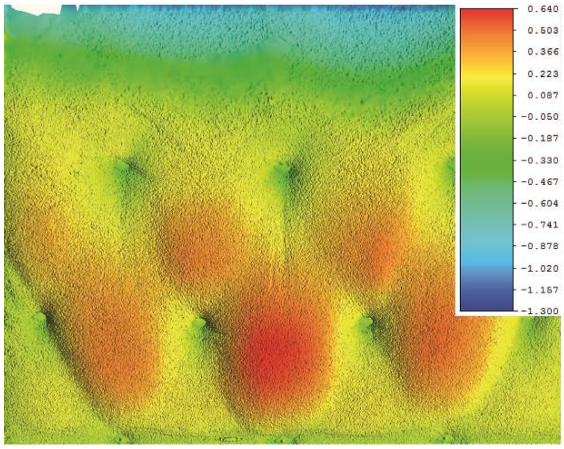

Figure 8. Test no. 13, TECCO® G65/4 + P33, nail grid 3.5 x 3.5 m, round gravel 0 - 63 mm, α = 60°.

The differences between figure 7 and figure 8 are the soil material used and the mesh. If a soil material with better interlocking properties and a much stronger steel wire mesh with identical mesh size and form are installed, much less deformation is to be expected.

The large-scale field tests also show the positive influence of the installation of the spike plates in previously-created recesses. Creating troughs makes it possible to actively stretch the mesh during installation. This significantly reduces deformations when lifting the steel frame, which makes a significant effect on the load bearing capacity of the entire system.

The mesh geometry in conjunction with the transmission of force from the mesh to the nail anchoring system also plays an important role. Since the introduction of high-tensile steel wire meshes with rhombus-shaped holes around the end of the 1990s, a nail grid was deliberately recommended whose nail rows are arranged laterally at an offset of half the horizontal distance between nails. Previously, square nail grids modeled after conventional rope nets were common.

If horizontal nail distance "a" is set to be identical to nail distance in fall line "b", a field of "a x 2b" is stretched between the nails. When observing the transmission of force from nail to nail (figure 6), it becomes clear that it follows the mesh geometry. Supported by the most direct force distribution possible, this fact has a positive effect on the load bearing capacity and deformation behavior of such flexible systems.

7. Verification of RUVOLUM dimensioning concept

The RUVOLUM dimensioning concept was developed on the basis of many years of experience in the area of flexible slope stabilization systems and was verified in 2000 using only model tests. The large-scale field tests performed in the scope of the CTI research project make it possible for the first time to examine the theoretical model approach and the underlying assumptions under realistic conditions and using repeatable tests. Figure 9 shows a two-body sliding mechanism which is trying to slide out between the nails and is prevented by the mesh cover and nails (Rüegger et al. 2000). Figure 10 illustrates the cross section of the unstable block under the stabilizing influence of the lateral spike plates. The fracture mechanism decisive for dimensioning has a width "a_{red}".

The graphic analysis of the laser scan shows good agreement with the model approach in accordance with the RUVOLUM concept. Comparative calculations are now to be performed. When doing so, a differentiation has to be made between the dimensioning situation while taking the corresponding partial safety factors according to EUROCODE 7 into account and the state of failure.

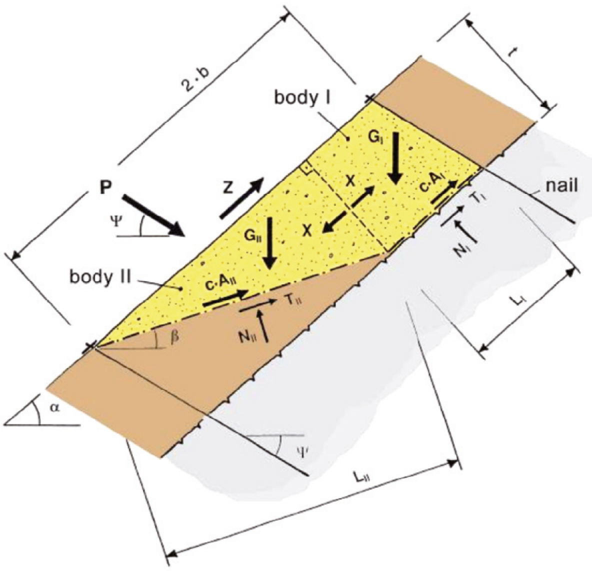

Figure 9. Two-body sliding mechanism in the examination of instabilities near the surface in accordance with the RUVOLUM concept.

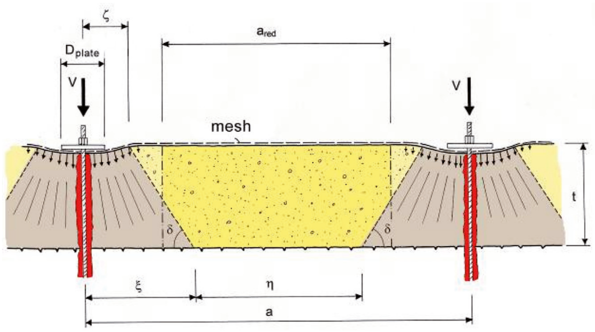

Figure 10. Reduced cross section as a result of the stabilizing influence of the lateral spike plates or nails in accordance with the RUVOLUM concept.

For the back-calculation, the results of large-scale field tests no. 11 using TECCO® G65/3 steel wire mesh in combination with type P33 spike plates and type GEWI D = 32 mm nails with a rusting away of 4 mm on the diameter are to be used as an example. The nail grid was 3.5 x 3.5 m. The soil material was broken-up sandy gravel made of recycling material.

The first movements near the surface occurred at an inclination of α = 53° (figure 11, left). The mesh was then punctured at α = 80° (figure 11, right).

If the flexible slope stabilization system used in test no. 11 is measured based on the RUVOLUM concept in accordance with EUROCODE 7, a maximum slope incline of α = 50° results. If the nail grid is reduced to 3.40 x 3.40 m, the permissible slope incline is increased to α = 53°.

Figure 11. Test no. 11 TECCO® G65/3 + P33, nail grid 3.5 x 3.5 m, sandy gravel 0 - 63 mm, α = 53°, first slides close to the surface (left) and at failure at α = 80° (right).

The results of the back-calculation correlate quite well with the situation in which the first instabilities close to the surface were observed.

If all partial safety factors are set to 1.00, the radius of the pressure cone increased to 0.30 m, the load bearing capacity of the mesh at point-by-point application of force at the upper nail with Z = 30 kN is fully utilized and if the nail inclination is assumed to be perpendicular to the slope surface as before, the break is calculated to occur at a slope of α = 76°. This result also agrees very well with the test results.

8. Different safety systems

In addition to mesh covers with rhombus-shaped openings, hexagonal steel wire meshes with and without vertical ropes and heavy chain-link mesh were tested. Depending on the mesh geometry, the significant differences in the load bearing capacity had to be determined while doing so.

Figure 12 shows a hexagonal steel wire mesh with a mesh size of 80 x 100 mm and a wire diameter of 2.7 mm combined with vertical ropes with a diameter of 8 mm at distances of 30 cm to each other. The 16 - 32 mm round gravel was used as soil material. The nail grid was 3.5 x 3.5 m. As the analysis of the laser scan shows, it was not possible or only partially possible to carry off the loads to the lateral nails due to the vertically dominating structure. A concentration of load and larger deformations in the base area of the slope were the consequences.

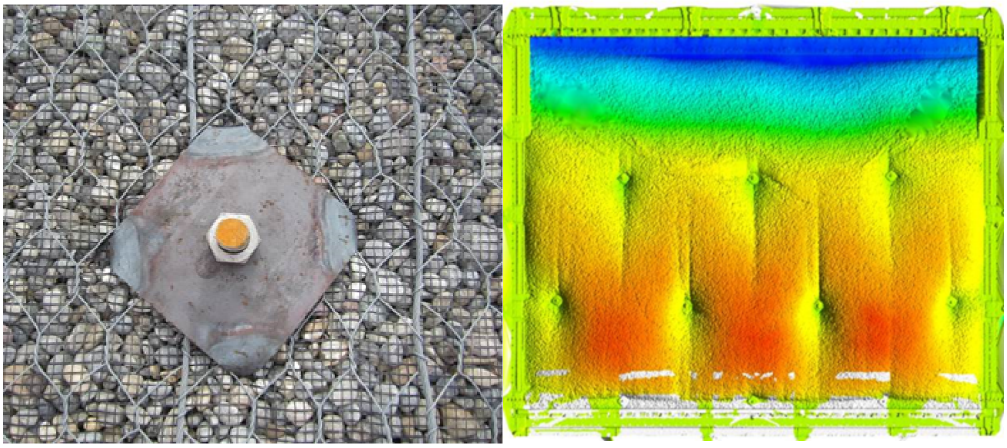

Figure 12. Test no. 7, hexagonal steel wire mesh with vertical ropes in distances of 30 cm, nail grid 3.5 x 3.5 m, round gravel 16 - 32 mm, α = 60°.

The test assembly for test no. 8 corresponded to that of test no. 7. However, a heavy chain-link mesh with a mesh size of 50 x 50 mm and a wire diameter of 4.6 mm with spike plates adapted to this was used as a mesh cover. Figure 13 shows the mesh used. As predefined by the structure of the mesh, it tries to carry the forces off to the side under around 45°, as shown by the blue dotted line in figure 13. If the same nail grid is used as with other tests, the force vectors starting from the upper nail do not meet directly. The force is transferred by redistributions, resulting in large deformations. To improve the situation, the nail arrangement must be adapted to the structure of the mesh or the distance between the nails must be reduced correspondingly in the fall line.

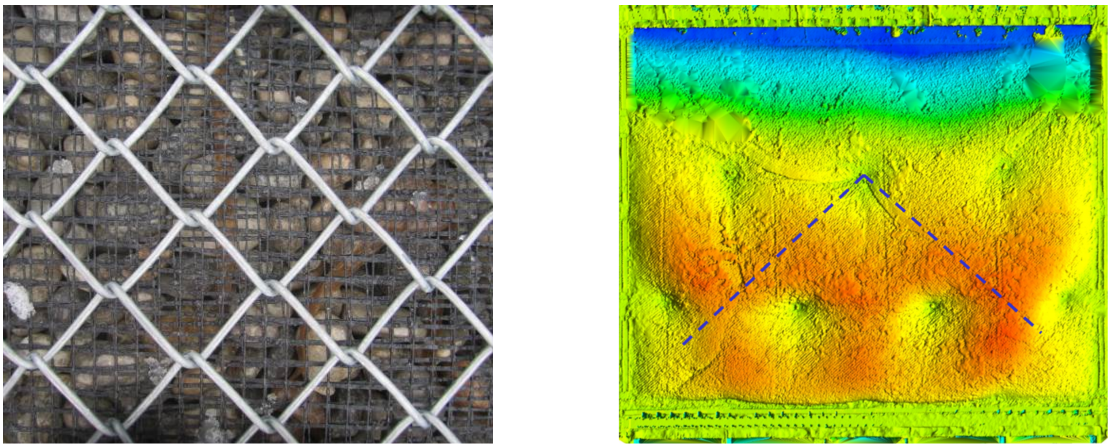

Figure 13. Test no. 8, heavy chain-link mesh 50 x 50 / 4.6 mm, nail grid 3.5 x 3.5 m, round gravel 16 – 32 mm, α = 60.

9. Conclusions

The large-scale field tests performed create an ideal foundation for a better understanding of the load bearing capacity of flexible slope stabilization systems as well as for further developing them and adapting them to project-specific requirements.

The size of the test frame seems to have been well-selected for simulating instabilities near the surface. In supplementary tests, additional results on impacts to the nails and especially in the nail head area will be gathered.

It was possible to verify the RUVOLUM dimensioning concept. The results agree well with the test results and the experience gathered over the last 15 years. They are based on a model approach which illustrates the real conditions in a simplified but sufficiently exact manner.

References

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