Results of large-scale testing of high-tensile steel meshes and soil nails for ground surface support and validation of modelling software

Roberto Luis Fonseca, Gonzalo Díaz Trillos

Geobrugg Group

gonzalo.diaz@geobrugg.com

Abstract

The stability of newly cut or natural slopes is an important issue of geotechnical engineering. Regardless of the scale of the project, the design and the execution must assure maintenance-free and, more importantly, safe utilisation of the slope. Nowadays, a geotechnical engineer can choose from several different, available slope stabilisation methods. Nevertheless, one of the most frequently chosen methods is soil nailing in combination with flexible facing (Luis-Fonseca, 2010). In this configuration, the soil nails are designed to stabilise deep-seated instabilities, while localised instabilities must be stabilised by the strong flexible facing, typically represented by high-tensile steel wire mesh. In order to assure proper slope stabilisation, the soil nails and the flexible facing must act as one integrated system. Such a system has been lately tested in large scale within this R&D project supported by the Swiss Institute for Technology and Innovation (CTI). The large-scale setup, widely described in Cała et al (2013), consisted of an inclinable large box (12 × 10 × 1.2 m), soil material, nails, high-tensile steel wire mesh, steel plates (linking nail heads and mesh), connection clips (linking two sheets of mesh) and boundary ropes. The entire setup was lifted on one side to imitate the slope inclination. While lifting the box up several measurements were taken (e.g. tension forces and bending in the nails or mesh displacement).

In total 31 large-scale tests were conducted, at first to check the testing setup and later to test the interactions of the nails and high-tensile steel mesh, which were put together in different arrangement and configurations. The most important testing variables were soil material, nail pattern, type of steel wire mesh and connection plate. The main aim of this paper is to present the analysis of the performance of three meshes composed of 2, 3 and 4 mm diameter wire, tested in comparable conditions (the same soil conditions, nail pattern and connection plate). The purpose of this analysis was to show the distinction in bearing capacity and range of deformation of meshes produced from the same steel high quality but of different wire diameter. This analysis was also used for the purpose of validation of already existing dimensioning concept based on lab tests.

1 INTRODUCTION

Superficial slope stabilisation using flexible facings has been in use for more than 30 years. Firstly, the slope surface was stabilised using wire rope nets, combined with gabion meshes and erosion control mats. Rather than using global safety calculations, problems with local, superficial instabilities were usually solved based on the rule of thumb. In such cases, the choice of facing, nail type and nail pattern was dictated by the intuition of an engineer and was not supported by any kind of geotechnical design. That situation changed about two decades ago when the dimensioning concept for shallow slope instabilities was developed. From that day on, one can easily model the superficial slope stabilisation system and adapt the nail pattern to local slope conditions. The dimensioning is available as an online tool that makes the calculations even easier and faster. Lately, the dimensioning concept was verified in series of large-scale tests in the frame of research and development project founded by Swiss Commission for Technology and Innovation (CTI). The large-scale tests allowed also the development of new flexible facing systems.

2 OBJECTIVES

The main goals of this paper are to present the comparison and optimisation possibilities of the flexible facing systems. These considerations are based on the results of dimensioning concept and large-scale tests. Therefore, firstly, the flexible facing systems are introduced, followed by short description of the dimensioning concept, the online tool and the 1:1 testing method.

3 FLEXIBLE FACING STABILISATION SYSTEMS

The flexible facing systems are always combined with soil nailing. In general, the flexible facing system is a composite of three steel elements: wire mesh, plates and connection clips. The role of connection clips is to sew one mesh panel to another in such way that this connection will be at least as strong as the mesh itself. On the other hand, the mesh and the plates always act together. The mesh tightly covers the slope surface and takes the entire load from sliding soil mass and transmits it through the steel plate to the anchorage system. Since the performance of the whole system depends directly on the connection between the mesh and the plate, there is a lot of attention given to make this connection as efficient as possible. The most important strength characteristics of flexible facing systems, utilised also in dimensioning concept, are punching resistance on the upper edge of the plate and shearing resistance on the contact between the mesh and the plate. These characteristics are usually specified in laboratory investigations. This critical bearing resistance was also checked within the large-scale tests. The elements of flexible facing systems used are standard components of the Tecco® system: three different mesh types, two different plate types and one, unified connection clip. The used mesh is a diamond-shaped chain-link with the dimensions of 83 × 143 mm of a single mesh and an aperture of 65 mm. The mesh is produced out of 2, 3 and 4 mm high-tensile steel wires (≥ 1,770 MPa). The steel plates are two types P33 (330 × 205 × 7 mm) and P66 (667 × 300 × 7 mm). Table 1 presents the combinations of the mesh and the plates used within the project, together with their characteristics of punching and shearing-off resistance.

Table 1. Punching and shearing-off resistance of meshes and plates combined in flexible facing systems investigated within research project

Mesh	Wire ϕ[mm]	Plate	Punching resistance [kN]	Shearing-off resistance [kN]
G65/2	2	P33	40	10
G65/3	3	P33	90	30
G65/3	3	P66	120	45
G65/4	4	P33	140	50
G65/4	4	P66	185	75

4 DIMENSIONING OF FLEXIBLE FACINGS STABILIZATION SYSTEMS

4.1 The concept

The dimensioning concept, described in Cała et al. (2012), is a simplified method for calculation of superficial slope stabilisation, based on limit equilibrium method. The first assumption is that all the soil nails are installed in regular rhomboidal pattern (figure 1). The dimensions of the rhomb created by the nails are $a \times 2b$, where a is the horizontal nail distance and $2b$ is the distance between next nails in the line of the slope. The dimensioning concept assumes two kinds of superficial failure mechanism. The first mechanism assumes that the whole superficial layer, parallel to the slope surface, slides down. In this case, the calculated soil body has dimensions of nail pattern $a \times b$ and the thickness t of sliding soil layer (figure 2a). The second mechanism assumes that there is single-body or two-body wedge-like failure mechanism. This time, the sliding body is located among four nails and has dimensions of $a \times 2b$ and t (figure 2b). The thickness of an unstable soil layer varies usually between 0.5 and 2.5 m, and it is either indicated by slope investigations or assumed based on engineer's experience.

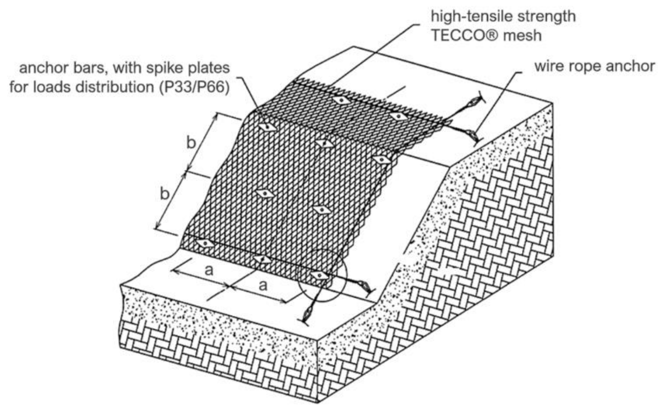


Figure 1. Arrangement of soil nails on the slope in regular rhomboidal pattern.

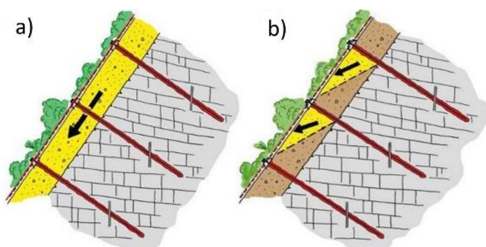


Figure 2. types of failure mechanism: a) layer parallel to the slope; b) wedge-like single or two-body mechanism depending on the vertical distance between nails.

The dimensioning concept investigates the equilibrium of the soil body and the limit states of the systems, based on 2D geometry considering the failure condition of Mohr – Coulomb. In such cases, five so-called proofs of bearing safety must be checked. In case of slope-parallel instabilities; (figure 2a), the proofs of safety are: 1) proof of the nail, against sliding-off, a superficial layer parallel to the slope 2) proof of the mesh against punching; 3) proof of the nail to resistance of the nail to combined stress. In case of localised instabilities between the nails (figure 2b), the proofs that have to be checked are: 4) proof of the mesh against punching force P on the upper edge of the plate; 5) proof of the mesh to selective transmit of the force Z into the nail (figure 3).

The last two proofs of safety are the important ones from the perspective of flexible facing system. In such a situation, an unstable soil mass is sliding down the slope, creating deformations above the lower nail and pushing on the upper edge of the spike plate fastened on this nail. The mesh is being tensioned and pulled down on the upper nail in the same cross-section. Figure 3 presents schematic the two-body wedge-like failure mechanism with deformations, punching force P and shearing-off force Z shown in the figure 3. This theoretical sliding mechanism was confirmed by numerous field observations and the large-scale tests (figure 4).

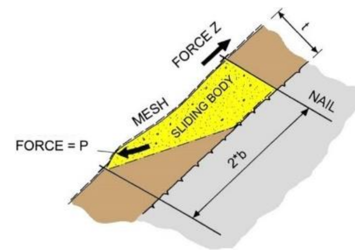


Figure 3. The schematic two-body wedge-like failure mechanism with deformation of the mesh, punching force P and shearing-off force Z

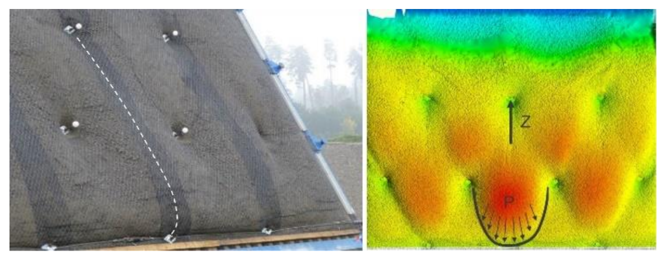


Figure 4. Test site observations of the deflection of flexible system: a) dashed line traces the deflection; b) laser scanner shows the sliding mechanisms (punching force P and shearing-off force Z.

4.2 Design on-line tool

The dimensioning tool is basically a software version of previously described dimensioning concept. It's available online at Geobrugg website (Roduner, 2019). With use of a tool one can easily enter and change all the parameters needed to properly calculate the stability of superficial soil layer. These parameters are as follows: soil properties, slope angle, thickness of the superficial layer, type, inclination and pattern of the soil nail and of course type of the flexible facing system. Additionally, one can consider external loads of earthquake and streaming pressure. The calculations can be adapted to appropriate standards by changing the safety factors. The dimensioning tool enables optimisation of the superficial slope stability calculations in different ways. Assuming given soil properties, one can change the type of flexible facing system and the nail pattern. Usually, using stronger flexible facing would result in bigger distance between the nails. Another optimisation possibility is changing of the slope inclination. This, nevertheless, is usually restricted by the lack of space or legal regulations.

5 LARGE-SCALE TESTS

The large-scale testing was the main part of research and development project supported by Swiss Institute for Technology and Innovation (CTI). In total thirty-one large-scale tests were conducted within the testing period between 2012 and 2014 in a quarry in Winterthur, Switzerland (Baraniak, 2014). The main goals of large-scale tests were: a) increasing knowledge about the interaction of soil and flexible system; b) checking the reliability and validation of the assumptions of the dimensioning concept; c) verification and confirmation of punching and shearing-off bearing resistances of flexible systems, After optimisation of the test setup the following experiments were conducted in a repetitive way to guarantee reliable and comparable experimental results. All experiments were conducted until the limit state of flexible facing was reached. The test setup was an artificial slope represented by an inclinable steel frame (12 × 10 × 1.2 m), (figure 5) which could be raised on one side by the crane in order to simulate the slope angle. In order to analyse the behaviour of flexible facing systems in different soil conditions, two materials with different strength parameters were chosen. Both soils were classified according to USCS Soil Classification System. The first soil is a poorly graded gravel (GP) and it's a mixture of 16-32 mm diameter round grains with internal friction angle of 33ºs. The second soil is a poorly graded gravel with silt (GP-GM) with size between 0-63 mm, and internal friction angle of 38º. To keep the soil material inside the frame its inner side was faced with wooden planks. The soil filling up the box was slightly distributed across the box by small crawler and non-compacted.

Figure 5. Test setup before the rupture of flexible facing and frame sizes and box frame empty

The nails used in tests were threaded steel bars (ø 32 mm), encased by a corrugated PVC tube (ø 100 mm) and cemented to simulate grouting. The nails were installed in regular rhomboidal patterns of 2.5 × 2.5 m, 3.0 × 3.0 m and 3.5 × 3.5 m. Some of them were equipped with strain gauges. All the nails were fixed to the steel frame with steel foot plates. Note that the measured stresses in the nails were quite similar, from place to place into the elements equipped with strain gauges.

The inclination of the test setup was measured constantly in order to have one reference scale for comparison of different flexible facing systems tested in varying conditions. The inclination was measured with an electrical inclinometer from company Tuck, with measuring resolution ≤0.14º and possible measuring range 0-360º. The inclination sensor had to be calibrated directly before each test. In order to double-check the inclination measurement, a simple free-weight goniometer was attached to frame and inclination scale was marked on the skid of the box.The displacement of the flexible facing systems were measured at every inclination step (0, 30 to 85º in every 5º) by pulse laser scanner. In general, the laser scanner measures distance by illuminating a target with a laser and analysing the reflected light. In our case, the values of displacements measured at certain inclination were later deducted from the values of the displacements at the initial state. The values of the maximum displacements were calculated from the whole area of the box. In order to avoid errors in the measurements the maximum displacement value was defined as the maximum displacement of an area of at least 0.25m^2. The horizontal and vertical angular resolution of the laser scanner was set to 0.02º, resulting in a density of 2×10^4 points / m^2 at 20 m distance and 1×10^4 points / m^2 at 30 m distance and the accuracy of measurement of 7 and 10 mm, respectively.

6 TEST RESULT

This section presents the comparison of results achieved from the calculations in dimensioning concept and the large-scale tests. The most quantitative and reliable unit for such comparison is the failure inclination of slope. In case of the dimensioning concept, the failure inclination of the superficial slope means that one or more of proofs of bearing safety of flexible facing are not fulfilled. On the other hand, in case of tests, the failure means that the flexible facing got ruptured around the nail heads as expected and the test could not be continued. Ground failure (soil) without reinforcement occurs, when the value of angle of internal friction is overcome.

All calculations with the online tool were done using the same mesh types, soil strengths and nail patterns as used within large-scale tests. Moreover, the calculations were done with all safety and partial factors (cohesion, friction angle, positive and negative loading, etc.) set to 1.0 (means breaking level). Since the thickness of the test setup was 1.20 m, the same thickness of the soil layer was assumed in the calculations.

The graphs in figure 6 and 7, present the failure inclination depending on punching resistance of the flexible facing, tested and calculated with nail pattern 3.0 × 3.0 m and 3.5 × 3.5 m, respectively. The solid lines represent the inclination values calculated with online tool, while the dashed lines represent the inclination values measured during tests. Due to lack of information from the tests in round gravel with 3.5 × 3.5 m nail pattern, the failure inclination values were partly estimated.

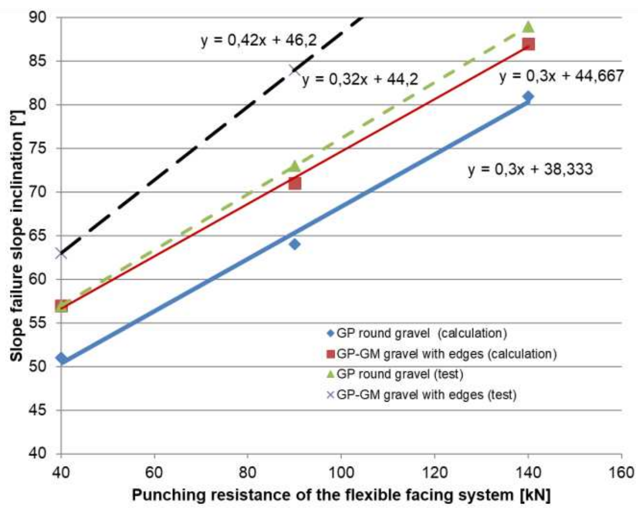


Figure 6. The comparison of failure inclination slope depending on the punching resistance of flexible facing system tested in large-scale tests and calculated with dimensioning concept. Tests and calculations with nail pattern 3.0 × 3.0 m

The observations made on failure inclination show that for the same mesh, regardless of the soil conditions and nail pattern, as general rule the values of the inclination measured within the tests are higher than the one calculated with online tool. On the other hand, the difference in the failure inclination between measured and computed values increases always together with the strength of the flexible facing. Figure 6 shows that the difference between calculated and measured values of failure inclination, with nail pattern 3.0 × 3.0 m, rises from 9 to 11% and 8 to 13% in the cases of testing of round gravel and sandy gravel, respectively. On the other hand, in the trials with 3.5 × 3.5 m nail pattern, the difference between calculated and measured values varies between 16 to 22% and 18 to 25% in case of round gravel and gravel with silt, respectively (figure 7).

Another interesting observation is that the difference in the failure inclination for calculated and measured values does not depend on the nail pattern. In case of the calculated values the difference was 10% and did not change with increasing punching resistance of the flexible facing system. In case of measured values (and partly predicted), the difference of the failure inclination increased together with the strength of the facing of about 10 to 16%.

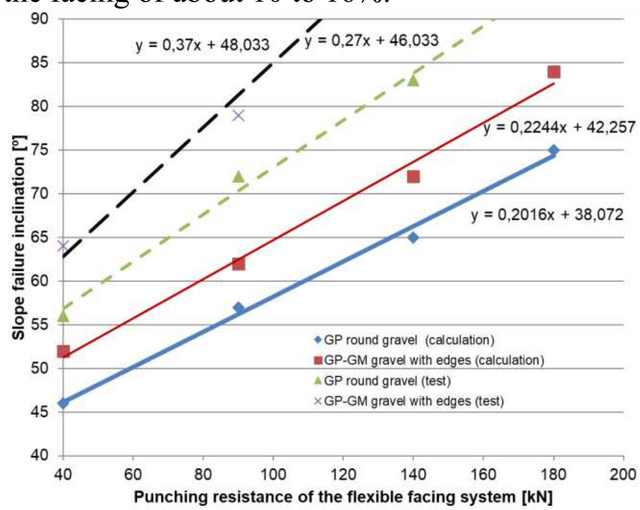


Figure 7. The comparison of failure inclination slope depending on the punching resistance of flexible facing system tested in large-scale tests and calculated with dimensioning concept. Tests and calculations with nail pattern 3.5 × 3.5 m

In order to analyse the load bearing capacity and displacement behaviour of flexible slope stabilisation systems, laser scans at a steel frame inclination of 60° (average value of common road slopes) are compared with one another in the following. Figure 8 shows the measured displacement 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 × 3.5 m with GEWI D = 32 mm nails, the maximum value of the displacement observed is 0.5 m. Figure 9 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 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, in this case the maximum value of the displacement observed is 0.55 m. The stronger mesh is somewhat stiffer under the same conditions. It is subject to less displacement and the soil material slides downwards to a lesser degree.

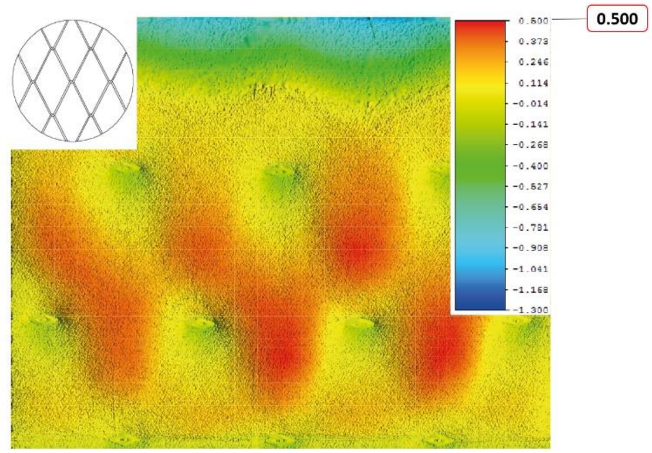
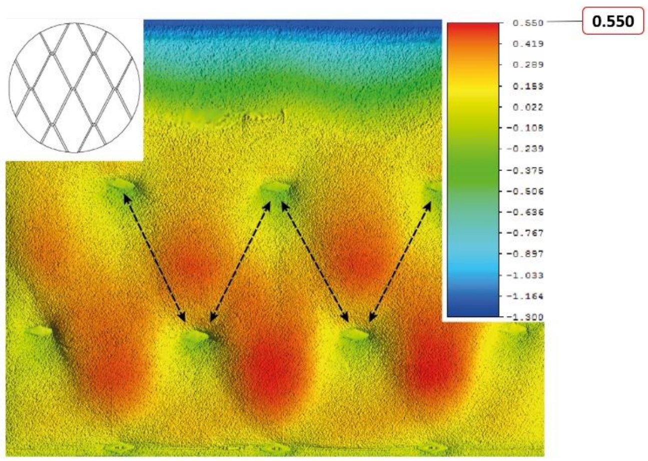


Figure 8. Test 12, Displacement (m) of the Tecco® mesh G65/4 + P66, nail grid 3.5 × 3.5 m, round gravel 16–32 mm,



α = 60°

Figure 9. Test 14, Displacement of the mesh (m) Tecco® G65/3 + P66, nail grid 3.5 × 3.5 m, round gravel 16–32 mm, α = 60° dashed lines shows, that the horizontal offset nail, contribute to the rational transmission of force from nail to nail.

Comparing figure 9 with 10, 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, is used a high-tensile steel wire mesh with a wire diameter of 2 mm and a longitudinal tensile strength of at least 65 kN/m.

The stabilising lateral influence of a smaller spike plate is weaker than with a larger one with enough bending stiffness. Furthermore, a somewhat weaker mesh under the same limiting conditions is somewhat more stressed, which becomes clear due to somewhat larger displacements with a wider bulge which slides downwards to a larger degree. In this last example the maximum value of the displacement observed is 0.64 m.

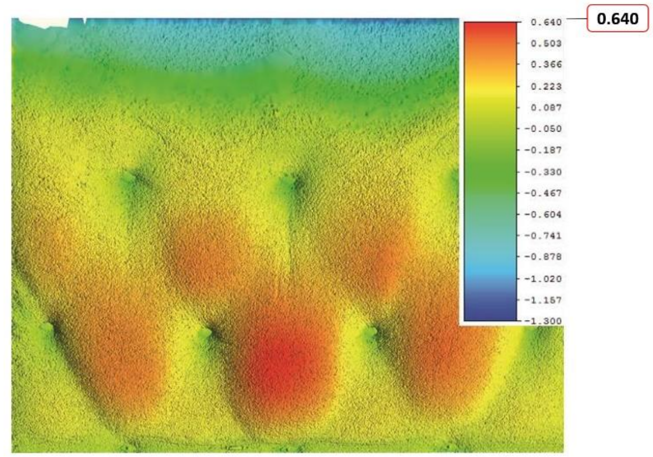


Figure 10. Test 17, Displacement (m) of the Tecco® mesh G65/2 + P33, nail grid 3.5 × 3.5 m, round gravel 16–32 mm, α = 60°

The differences between figure 10 and 11 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, less displacement is to be expected.

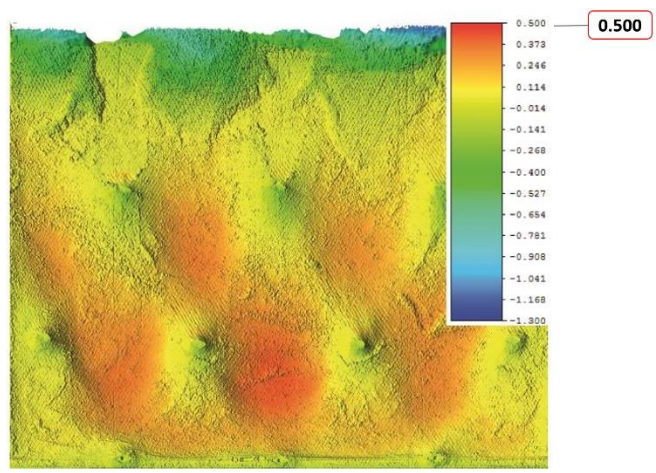


Figure 11. Test 13, Displacement of the mesh Tecco® G65/4 + P33, nail grid 3.5 × 3.5 m, sandy gravel 0–63 mm, α = 60º

The large-scale 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 displacements 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 modelled 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 × 2b” is stretched between the nails. When observing the transmission of force from nail to nail (figure 10), 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 behaviour of such flexible systems.

7 VERIFICATION OF RUVOLUM DIMENSIONING

The Ruvolum® dimensioning concept (Rüegger, 2000) was developed based on many years of experience in the area of flexible slope stabilisation systems and was verified in 2000 using only model tests. The large-scale 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 quasi-realistic conditions and using repeatable tests. Figure 12 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, 2000).

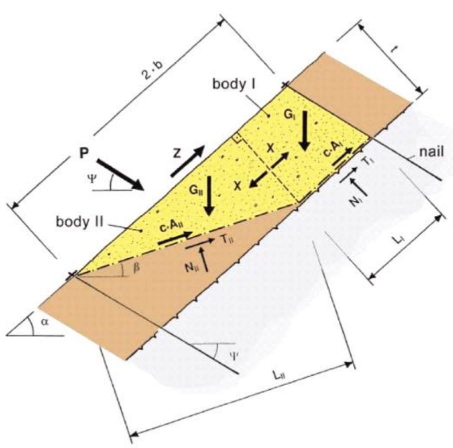
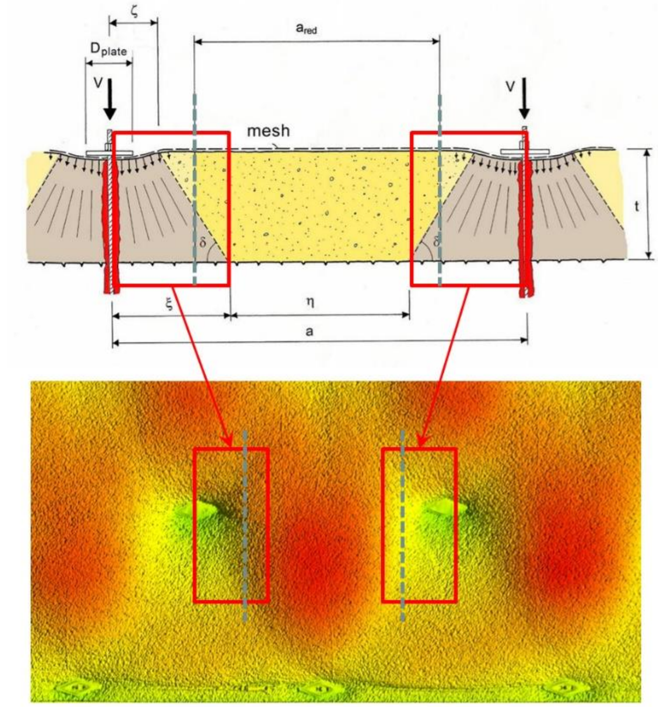


Figure 12. Two-body sliding mechanism in the examination of instabilities near the surface in accordance with Ruvolum®.

Figure 13 illustrates the cross section of the unstable block under the stabilising 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 must 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 13. Reduced cross section as a result of the stabilising influence of the lateral spike plates or nails in accordance with the RUVOLUM concept

For the back-calculation, the results of large-scale 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 × 3.5 m. The soil material was broken-up sandy gravel made of recycling material previously described. The first superficial movements in all the area can be observed at an inclination of α = 53° (figure 14, left). The mesh was then punctured at α = 80° (figure 14, right).

Figure 14. Test 11 Tecco® G65/3 + P33, nail grid 3.5 × 3.5 m,

sandy gravel 0–63 mm, α = 53°, first superficial movements (left) and at failure at α = 80° (right).

If the flexible slope stabilisation system used in test No. 11 is modelled using the Ruvolum®

software in accordance with Eurocode 7 (that recommend partial safety factors: for the friction angle and the cohesion till 1.25, and for the model uncertainty 1.10), a maximum slope incline of α = 50° results. For example, if the nail grid is reduced to 3.40 × 3.40 m, the permissible slope incline is increased to α = 53°.

The results of the back-calculation with the software 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 ζ = 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 utilised and if the nail inclination is assumed to be perpendicular to the slope surface as before, the break -calculated by the software occur at a slope of α = 76°. This result also agrees very well with the test results.

8 CONCLUSIONS

The large-scale tests performed create an ideal foundation for a better understanding of the load bearing capacity of flexible slope stabilisation systems as well as for further developing them and adapting them to project-specific requirements. The diversity of tests carried out has also allowed to contrast the theoretical parameters and hypotheses used in the simulation, leaving the theoretical model duly calibrated. Although comparisons have been made under the same soil nail pattern and the same nail diameter, -which undoubtedly implies an identical support capacity-, it has been shown that to the extent that the resistance of the membrane is bigger, the displacement is less. Considering the practical constraints (crane 500t) the size of the test frame seems to have been well-selected for simulating superficial instabilities. In supplementary tests, additional results on impacts to the nails and especially in the nail head area will be gathered. The results presented within the present paper show that the failure inclination of the superficial layer of the slope depends strongly on the type of flexible facing used for the superficial stabilisation. The difference of the results achieved from the large-scale tests and the dimensioning concept vary between 8 and 25% and seem to confirm the correctness of the assumptions of the dimensioning concept. The Ruvolum® dimensioning concept based on lab tests seems to be on the safe side compared to the tests. Since the test setup presented, is the world’s first installation for artificially checking the slope superficial stability, the results achieved from the tests should be taken with certain stealth and should never be used as safety factors. In any case, it is highly recommended to incorporate safety factors for slope stability calculations.

9 REFERENCES

Baraniak, P. & Schwarz-Platzer, K. & Stolz, M. & Shevlin, T. & Roduner, A. 2014. Large scale field tests for slope stabilizations made with flexible facings. Kingston, Geohazards 6.

Cała, M. & Flum D. & Roduner A. & Rüegger, R. & Wartmann, S. 2012. Tecco® Slope Stabilization System and RUVOLUM® Dimensioning Method. Bad Langesalza: Beltz Bad Langesalza GmbH.

Cała, M. & Stolz, M. & Baraniak, P. & Rist, A. & Roduner A. & 2013. Large scale field tests for slope stabilizations made with flexible facings. Proceedings of EUROCK 2013 Wrocław, 23-26 September 2013. Rotterdam: Balkema.

Luis-Fonseca, R. 2010 Aplicación de Membranas flexibles para la prevención de riesgos naturales. Roperpo Editores

Roduner, A. 2019. TECCO Slope Stabilization System. Summary of Published Technical Papers 1998 – 2019.

Rüegger, R. Flum, D. & Haller, B. 2000. Hochfeste Geflechte aus Stahldraht für die Oberflächensicherung in Kombination mit Vernagelungen und Verankerungen. 2nd "Building in Soil and Cliffs" colloquium at the Technical Academy of Esslingen, Germany