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# High-tensile steel meshes used in slope stabilization systems, tested in first large scale field test application

Mailles en acier à haute résistance à la traction, utilisées dans les systèmes de stabilisation des pentes, testé une pleine échelle

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**ABSTRACT:** The slopes stability is an important issue of geotechnical engineering. The design and the execution have to assure maintenance-free and the safety. One of the most frequently chosen methods is the nailing in combination with flexible facing. The flexible facing is typically represented by high-tensile steel wire mesh. In order to assure proper slope stabilization, the nails and the flexible facing have to act as one integrated system. Such system has been lately tested in large scale within this R&D project supported by Swiss Institute for Technology and Innovation. The large-scale setup consisted of a large box (12x10x1.2m), soil material, nails, high-tensile steel wire mesh, steel plates, connection clips and boundary ropes. The entire setup was lifted up on one side. While lifting the box up several measurements were taken (e.g. tension forces and bending momentums in the nails or mesh deformation). In total 31 field tests were conducted, at first to check the testing setup and later to test the interactions among system components, using different arrangement and configurations.

**RÉSUMÉ :** La stabilité des pentes est importante dans l'ingénierie géotechnique. La conception et l'exécution doivent assurer le libre entretien et la sécurité. Une des méthodes les plus fréquemment choisis est le clouage en combinaison avec revêtement flexible. Le revêtement flexible est généralement représenté par des treillis métallique a haute résistance. Afin d'assurer une stabilisation adéquate de la pente, le clouage et le revêtement flexibles doivent agir comme un seul système intégré. Ce système a été récemment testé à grande échelle au sein du projet R&D assuré par Institut Suisse de Technologie et d'Innovation. La configuration à grande échelle, se compose d'une grande boîte (12 x 10 x 1,2 m), les matériaux du sol, des clous, maille de fil d'acier à haute résistance, plaques d'acier, des clips de connexion et cordes de délimitation. L'ensemble du montage a été élevé sur un côté. Tout en soulevant la boîte, plusieurs mesures ont été prises (par exemple. Les forces de traction et les moments de flexion dans les clous ou la déformation du maillage). Totalemnt 31 test ont été effectué sur le terrain, dans un premier temps pour vérifier la configuration du test et ensuite pour tester les interactions entre les composants du système, en utilisant différents arrangements et configurations.

**KEYWORDS:** slope stabilization, flexible facing system, Tecco®, Ruvolum®, large-scale slope test, high tensile strength mesh

## 1 INTRODUCTION

Surficial slope stabilisation using flexible facings has been in use for more than 30 years. Firstly, the slope surface was stabilised using wire rope nets, gabion meshes or erosion control mats. Rather than using global safety calculations, problems with local, surficial 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. Nowadays, the dimensioning concept is available as an tool that makes the calculations 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 FLEXIBLE FACING 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, back plates and connection clips. 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 puncturing resistance on the upper edge of the spike plate and shearing resistance on the contact between the mesh and the plate.

The elements of flexible facing systems used within the frames of this research project are standard components of the TECCO® system: three different meshes, two different plates and one, unified type of connection clip. The mostly used mesh is a diamond-shaped chain-link mesh with aperture of 65mm. The mesh is produced out of 2, 3 and 4 mm high tensile steel wires (1,770MPa). The steel plates are produced in two types: P33 (330×205×7mm) and P66 (667×300×7mm), Table 1.

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

Mesh	Wire diameter (mm)	Plate type	Puncturing resistance (kN)	Shearing-off resistance (kN))
G65/2	2	P33	40	10
G65/3	3	P33	90	30
G65/3	4	P33	140	50
G65/4	4	P66	185	75

### 3 DIMENSIONING OF FLEXIBLE FACINGS

#### 3.1 Dimensioning concept

The dimensioning concept, widely described in Cała et al. (2012), is a simplified method for calculation of surficial 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 failure surficial mechanism. The first mechanism assumes that the whole surficial layer, parallel to the slope surface, slides down the slope. The second mechanism assumes that there is single-body or two-body wedge-like failure mechanism.

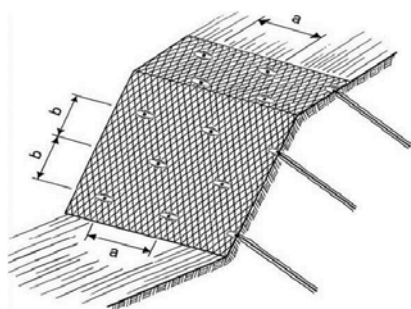


Figure 1. Arrangement of soil nails on the slope in regular rhomboidal pattern.

The thickness of an unstable soil layer varies usually between 0.5 and 2.0 m, and it is either indicated by slope investigations or assumed based on engineer's experience, described in 'TECCO Slope Stabilization System', Summary of Published Technical Papers 1998–2011. The dimensioning concept investigates the equilibrium of the soil body and the limit states of flexible facing systems and the soil nails, based on 2D geometry considering the failure condition of Mohr–Coulomb. In such cases, five so-called proofs of bearing safety have to be checked. The proofs of bearing safety that have to be checked depend on the type of failure mechanism. In case of slope-parallel instabilities; 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 puncturing; 3) proof of the nail to resistance of the nail to combined stress. In case of localised instabilities between the nails, the proofs that have to be checked are: 4) proof of the mesh against puncturing 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 2).

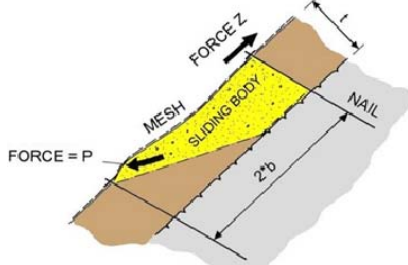


Figure 2. The schematic two-body wedge-like failure mechanism with deformation of the mesh, puncturing force  $P$  and shearing-off force  $Z$ .

The last two proofs of safety are the most 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. At the same

time the mesh is being tensioned and pulled down on the upper nail in the same cross-section. Figure 2 presents schematic the two-body wedge-like failure mechanism with deformations, puncturing  $P$  and shearing-off  $Z$  shown in the Figure 2.

Both the  $P$  and the  $Z$  values play an important role in the whole dimensioning concept. It is not possible to reduce the concept to a small scale size, like the tension force of the mesh for example which easily can be proofed by a small scale lab test of the mesh with a tensioning machine. But the total system interaction with plate, soil and flexible system resulting in a force on the mesh by the plate leading to the  $P$  and  $Z$  values can only be determined by a large scale experiment as close as possible to nature.

#### 3.2 Dimensioning tool

The online dimensioning tool is basically a digitalised version of previously described dimensioning concept. With use of a tool one can easily enter and change all the parameters needed to properly calculate the stability of surficial soil layer. These parameters are as follows: soil properties, slope angle, thickness of the surficial 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 values of safety factors.

### 4 LARGE-SCALE TEST

In total, 31 large-scale tests were conducted within the testing period between 2012 and 2014 in a quarry in Winterthur, Switzerland (Baraniak et al. 2014). The main goals of large-scale tests were: a) increasing knowledge about the behaviour and the interaction of soil and flexible facing; b) checking the reliability and validation of the assumptions of the dimensioning concept; and, c) verification and confirmation of puncturing and shearing-off bearing resistances of flexible facing systems, based on test site observations and back calculations.

Initial experiments of the test period allowed for observation and optimisation of the test setup, testing procedure and data acquisition method. After optimisation of the test setup the following experiments were conducted in a repetitive way to guarantee reliable and comparable experimental results. All individual experiments were conducted until the limit state of flexible facing was reached. The test setup was an artificial slope represented by a large-scale inclinable steel frame ( $12 \times 10 \times 1.2$  m), (Figure 3) 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 soil materials with different strength parameters were chosen. Both soils were classified according to Unified Soil Classification System (USCS). The first soil is classified as poorly graded gravel (GP) and it is a mixture of 16 mm and 32 mm diameter grains with internal friction angle of 33 degrees.



Figure 3. Test setup before the rupture of flexible facing.

Most of its grains are rounded and therefore the soil is called round gravel. The second soil is classified as poorly graded gravel with silt (GP-GM) with grain size between 0 and 63 mm, and internal friction angle of 38°. To keep the soil material inside the frame, its inner side was faced with wooden planks.

The nails used in tests were represented by threaded steel bars (ø 32 mm), encased by a corrugated PVC tube (ø 100 mm) and cemented to simulate the construction conditions. The nails were installed in the box in regular rhomboidal patterns of 2.5×2.5m, 3.0×3.0m and 3.5×3.5m. Some of the nails 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. The inclination was measured with an electrical inclinometer, with measuring resolution ≤0.14° and possible measuring range 0°–360°. The deformation of the flexible facing systems, were measured at every inclination step (0, 30 to 85° in every 5°) by pulse laser scanner. In order to avoid errors in the measurements the maximum deformation value was defined as the maximum deformation of an area of at least 0.25m<sup>2</sup>. The horizontal and vertical angular resolution of the laser scanner was set to 0.02°, resulting in a density of 2×10<sup>4</sup> points/ m<sup>2</sup> at 20m distance and 1×10<sup>4</sup> points/ m<sup>2</sup> at 30 m distance and the accuracy of measurement of 7 and 10 mm, respectively.

### 5 TEST RESULTS

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 surficial 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 anchor 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 software 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.

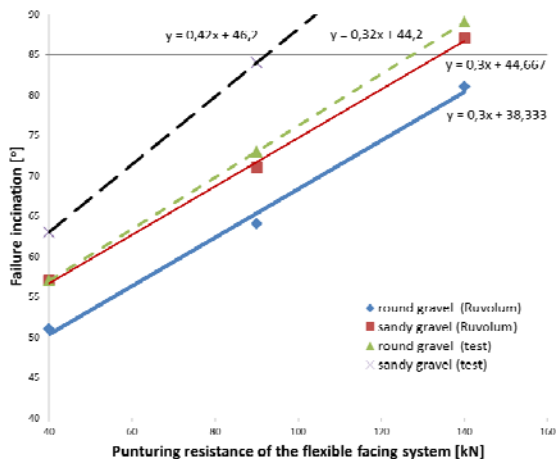


Figure 4. Tests and calculations with nail pattern 3.0 × 3.0 m

Figures 4 and 5 represent the failure inclination depending on puncturing resistance of the flexible facing, tested and calculated with nail pattern 3.0×3.0m and 3.5×3.5m, respectively. The solid lines represent the inclination values calculated with online tool, while the dashed lines represent the inclination slope 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 predicted.

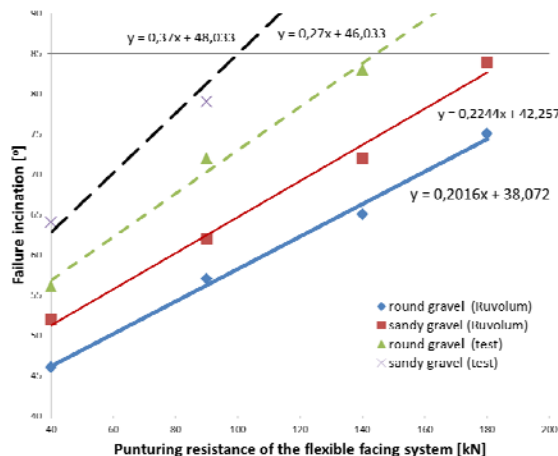


Figure 5. Tests and calculations with nail pattern 3.5 × 3.5 m

The difference in the failure inclination between measured and computed values increases always together with the strength of the flexible facing. Figure 4 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 3.5×3.5m nail pattern, the difference between calculated and measured values varies between 16 to 22% and 18 to 25% in case of round gravel and sandy gravel, respectively (Figure 5). These differences are mainly associated with some simplifications and model hypothesis, for example, the interaction between the mesh and nails is not considered. The model, although describes adequately the phenomenon, is slightly conservative, respect to the reality.

In order to analyse the load bearing capacity and deformation behaviour of flexible slope stabilisation systems, laser scans at a steel frame inclination of 60° (common road slopes) are compared with one another in the following. Figure 6 shows the measured deformation of a TECCO® G65/4 type high-tensile steel wire mesh with spike plate P66 with round gravel and a nail grid of 3.5×3.5m with GEWI ø 32mm nails, the maximum value of the deformation observed is 0.5m.

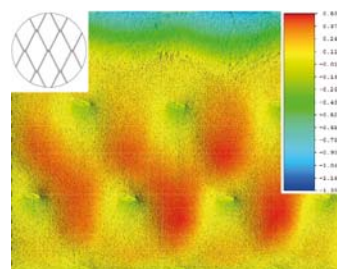


Figure 6. Test No. 12, measured deformation (m) of the TECCO® mesh (m) G65/4 + P66, nail grid 3.5×3.5m, round gravel 16–32 mm, α = 60°

Figure 7 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 150kN/m was used, in this case the maximum value of the deformation observed is 0.55m. 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.

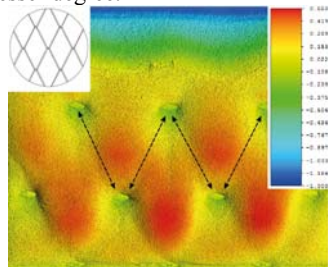


Figure 7. Test No. 14, measured deformation of the mesh (m) TECCO® G65/3 + P66, nail grid 3.5×3.5m, round gravel 16–32 mm,  $\alpha = 60^\circ$  dashed lines shows, that the horizontal offset nail, contribute to the rational transmission of force from nail to nail.

If you compare Figure 6 with Figure 7, 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, a high-tensile steel wire mesh is used with a wire diameter of 2 mm and a longitudinal tensile strength at least 65 kN/m. The stabilising 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. The maximum value of the deformation observed is 0.64 m.

Creating troughs makes it possible to actively stretch the mesh. The geometry in conjunction with the transmission of force from the mesh to the anchoring system also plays an important role. 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 7), 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 of such flexible systems.

## 6 VERIFICATION OF RUVOLUM® CONCEPT

The RUVOLUM® dimensioning concept (Rüegger et al. 2000) was developed on the basis of many years of experience. The large-scale tests make it possible examine the theoretical model approach and the underlying assumptions under quasi-realistic conditions. Figure 8 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).

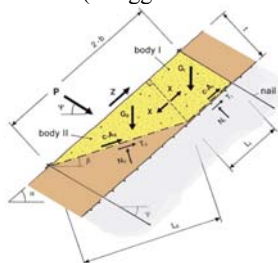


Figure 8. Two-body sliding mechanism in the examination of instabilities near the surface in accordance with the RUVOLUM® concept

For the back-calculation, the results of large-scale tests No. 11 (Figure 9) using TECCO® G65/3 steel wire mesh, in combination with type P33 spike plates and GEWI  $\phi 32$ mm nails, with a rusting away of 4 mm on the diameter, are to be

used as an example. The first superficial movements in all the area can be observed at an inclination of  $\alpha = 53^\circ$  (Figure 9, left). The mesh was then punctured at  $\alpha = 80^\circ$  (Figure 9, right). If the flexible slope stabilisation system used in test No. 11 is modelled using the RUVOLUM® software in accordance with EUROCODE 7 (recommends a partial safety factor: for the internal friction angle and the cohesion till 1.25, and for the model uncertainty till 1.10), a maximum slope incline of  $\alpha = 50^\circ$  results.



Figure 9. Test No. 11 TECCO® G65/3 + P33, nail grid 3.5×3.5m, sandy gravel 0–63 mm,  $\alpha = 53^\circ$ , first superficial movements (left) and at failure at  $\alpha = 80^\circ$  (right)

The back-calculation with the software correlate quite well the activities close to the surface observed. If all partial safety factors are set to 1.00, the radius of the pressure cone increased to  $\zeta = 0.30$  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 perpendicular to the slope surface, calculated by the software, the failure occur at a slope  $\alpha = 76^\circ$ , this result, also match very well with the test.

## 7 CONCLUSION

The large-scale tests performed create an ideal foundation for a better understanding of the load bearing capacity of flexible slope stabilisation systems. Considering the practical restrictions (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 present paper show that the failure inclination of the surficial layer of the slope depends strongly on the type of flexible facing. The differences of the results achieved from the large-scale tests and the dimensioning concept varies between 8 and 25%. This allows confirm that the model assumptions are right. The RUVOLUM® concept based on laboratory tests, it's on the safe side compared to the large-scale tests. The test setup is the world's first installation for artificially checking the surficial stability, the results achieved from the tests should be taken with some reserve and should never be used as add safety factors. It's always recommending the use of safety factors for slope stability calculations.

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