Large-scale experiments on deformation of flexible facings used for slope stabilization

P. Baraniak, K. Schwarz-Platzer & M. Stolz
Bern University of Applied Sciences, Switzerland, piotr.baraniak@bfh.ch,
T. Shevlin,
Geobrugg North America, LLC, Salem, OR, USA
A. Roduner
Geobrugg AG, Switzerland

ABSTRACT
Flexible facing systems consisting of high tensile strength steel wire mesh and soil nails are widely used for stabilizing steep soil and weathered rock slopes. Even though these systems have been used worldwide for decades, only few scientific studies on their design and optimization have been carried out and documented so far. Therefore, the primary objective of this study is to analyze the performance of such flexible facing systems and to describe the nature of failure mechanisms in the surficial layer of the slope.

The basis for the study was a series of field experiments with various flexible facing systems stabilizing an artificial soil slope consisting of an inclinable large-scale box (12 x 10 x 1.2 m). The steepness of the slope was simulated by raising one side of the box with a crane up to an angle of 85 degrees. This artificial slope was filled up with two different soil types and equipped with soil nails and steel wire mesh on the surface. During this procedure mesh deformations were continuously measured with laser scanner and recorded. The experiments were performed in order to investigate the behavior of the system under different soil conditions and configurations (i.e. nail spacing, mesh strength and type of spike plate).

In this paper the first results of measured mesh deformations, which depend on different flexible facings, are presented. This analysis highlights the interaction between soil nails and flexible facing used to stabilize shallow slope movements. The results of this research are the basis for a better design of the system and further optimization.

RÉSUMÉ
Les systèmes flexibles, consistant en un filet de haute résistance et des pointes d'ancrage, sont destinés à stabiliser les pentes raides ainsi que des pentes rocheuses érodées. Bien que ce type de stabilisation flexible des pentes soit utilisé dans le monde entier depuis plusieurs décennies, seulement quelques études scientifiques ont été menées sur le design et l'optimisation de la transmission des forces dans le sol. Pour cette raison, le but principal de cette recherche est d'analyser la performance du système flexible et de décrire les mécanismes de rupture dans les compartiments instables de la surface.

Un grand nombre d'expériences à l'échelle réelle a été réalisés avec le système flexible stabilisant une pente artificielle crée par une grande boîte inclinable (12 x 10 x 1.2 m). La raideur de la pente peut être réglée avec une grue capable de soulever la boîte sur un côté jusqu'à une inclinaison permettant d'atteindre 85 degrés. Cette pente artificielle a été remplie avec des sols divers et couverte à la surface par le système du filet de haute résistance et des pointes d'ancrage. Pendant les tests les déformations superficielles du filet flexible étaient enregistrées en continue. Le but de ces expériences était d'explorer le comportement du système flexible avec non seulement des conditions de sol divers mais encore des configurations différentes (intervalle de l'ancrage, résistance du filet et plaques à griffes).

Dans cette contribution nous présentons les premiers résultats des mesures de déformations du filet, qui sont influencés par la haute performance de celui-ci. Cette analyse souligne l'interaction entre l'ancrage et le système flexible utilisés pour stabiliser les glissements superficiels. Les résultats nous offrent une base permettant l'optimisation future du système flexible et son meilleur design.

1. INTRODUCTION

Examples of hundreds of slopes, successfully stabilized with flexible facing systems, prove the reliability and applicability of these stabilization measures (Figure 1). Even though the history of flexible facing systems started decades ago, only the recently developed measures seem to be working efficiently as self-standing systems (Cała, et al. 2012). This is possible only because all the elements of those systems are working together in order to transmit the load to the stable subsoil of the slope. Since the tensile strength and the puncturing resistance of tested flexible facing systems are known, the main goal of the large scale experiments was to gain the knowledge of the maximum deformations of the system, stresses occurring in the soil nails and the load transmission from the spike plate to the mesh and the subsoil. The focus of this paper is to analyze the behavior of flexible facing systems under different soil conditions and configurations (i.e. nail spacing, mesh strength and type of spike plate).

2. FLEXIBLE FACING SYSTEM ELEMENTS

Flexible facing systems consist of high tensile steel wire mesh, spike plates and soil nails. Depending on the slope conditions and the specific requirements these elements can be put together in different configurations.

Figure 1. Slope stabilized with high-tensile strength steel wire mesh

2.1 High-tensile strength mesh

One of the most important components of flexible facing systems is a high-tensile steel wire mesh (tensile strength of steel ≥ 1770 MPa) called TECCO®, presented in Figure 2. In general, it is a diamond-shaped chain-link mesh produced from 2, 3 or 4 mm steel wires. A single mesh opening has dimensions of 83 x 143 mm and aperture of 65 mm. This combination of wire diameter, opening shape and the unique steel parameters allows creating meshes with a longitudinal strength in a range of 65-250 kN/m.

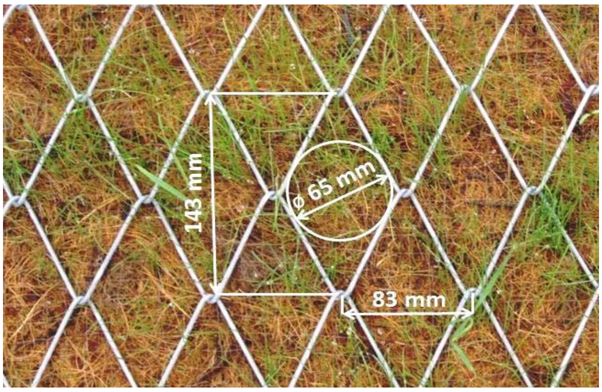

Figure 2. The shape and dimensions of high-tensile steel wire mesh G65/3

The performance of the mesh depends directly on the parameters of steel and the wire diameter. One important characteristic value of the mesh is its puncturing resistance. In general, the puncturing resistance is the bearing resistance of the mesh against the pressure strains occurring in an area of the spike plate, while soil is pushing on the mesh. In this case the puncturing resistance depends on strength of the mesh (steel parameters, wire diameter) and also on the connection area around the spike plate. Table 1 presents three different types of high-tensile steel wire mesh used during the experiments presented here. The high-tensile steel wire mesh reduces the slope deformations, stabilizes the slope surface and protects it against local failures. Moreover, the primary function of the mesh is to transfer all forces applied to it due to local failures of the soil onto the mesh and transferred to the nailing system.

Table 1. Specification of the high-tensile steel wire mesh

Specification of the high-tensile steel wire mesh				
Mesh type	Wire diameter	Minimum longitudinal strength of the mesh	Puncturing resistance depending on the type of the spike plate	
	[mm]	[kN/m]	[kN]	
G65/2	2	65	80	P33
G65/3	3	150	180	P33
			240	P66
G65/4	4	250	280	P33
			370	P66

2.2 Spike plates

Another primary component of flexible facing systems are the system spike plates which are steel plates connecting the mesh with the nailing system. The steel spike plates are produced in two types P33 (330 x 190 x 7 mm) and P66 (660 x 290 x 7 mm). They are designed to allow taking all stresses coming from the subsoil, pushing onto the mesh and transmitting them to the soil nails. Figure 3 shows the P33 spike plate properly fastened on the high-tensile steel wire mesh.

Figure 3. Spike plate type P33 (300 x 190 x 7 mm)

2.3 Soil nails

The soil nails (rock bolts) are integral components of flexible facing systems and may be represented by hollowed or solid bars with the external diameter of about 25 to 40 mm (Phear, et al. 2005). Depending on the individual slope conditions the soil nails are installed in 1.5 m up to 3.5 m distance from each other in regular triangular patterns defined by horizontal (a) and vertical (b) distance (Figure 4). The main role of the soil nails in geotechnical engineering is to stabilize the slope against global failures. Nevertheless, they are often used in combination with flexible facings to protect slopes also against local failures. In this case the role of the soil nails is to properly fasten and pre-tension the steel mesh onto the surface of the slope. The mesh is pre-tensioned by tightening the nut, thereby applying a load to the nail head and pushing the spike plate and the mesh into depression around the nail heads and onto the subsoil. Proper mesh pre-tensioning creates a stabilized zone around the nail and reduces the potential deformation of the mesh and shallow soil movements on the slope surface.

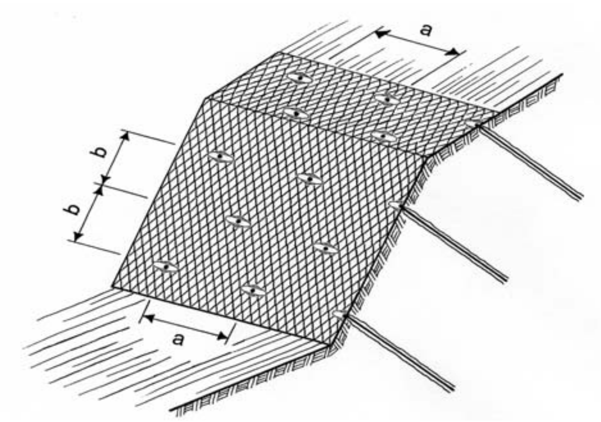

Figure 4. Triangular nail arrangement for the slope stabilization with flexible facing systems

3. EXPERIMENTS

Initial experiments allowed for observation and optimization of the test setup, testing procedure and data acquisition method. After optimization of the test setup the following experiments were conducted in a repetitive way to achieve reliable and comparable experimental results. All individual experiments were conducted until the ultimate inclination of the setup was reached (85 degrees) or until the ultimate capacity of the whole system or one of its elements broke.

3.1 Soil properties

To analyze the behavior of flexible facing systems in different soil conditions two materials with different parameters were chosen (Table 2). Both materials were classified according to USCS Soil Classification System. The first soil is classified as poorly graded gravel (GP) with grains size 16 and 32 mm and internal friction angle of 33 degrees. 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 grains size between 0 and 63 mm, and internal friction angle of 38 degrees.

Table 1. Properties of the soil types used in experiments

USCS Symbol	USCS Definition	Paper Definition	Friction angle [º]	Cohesion [kPa]
GP	Poorly graded gravel	Round gravel	33	0
GP-GM	Poorly graded gravel with silt	Gravel with silt	38	0

3.2 Experimental setup and procedure

Figure 5 shows the test setup which was an artificial slope represented by the inclinable full-scale box (12 x 10 x 1.2 m) raised on one side by a crane up to an angle of 85 degrees to simulate the slope angle. The soil nails, represented by threaded steel bars (ø 32 mm), previously equipped with strain gauges, were grouted and installed in the box in order to acquire the information about deformations and stresses during the experiment. The soil nails were installed in regular triangular patterns of 2.5 x 2.5 m, 3.0 x 3.0 m and 3.5 x 3.5 m. In the next step the box was filled in with the soil (without compaction) and covered with erosion control mat. As the last layer the high-tensile steel wire mesh was laid out onto the surface and attached to the nailing system with the steel plates and tensioned. The flexible facing systems consisted of the combination of two different spike plates and three different mesh types.

Each experiment started with careful check of the test setup. In the next step the instrumentation was inspected and the inclination sensor was calibrated. Prior to lifting the artificial slope box the data acquisition device was switched on and the acquisition software was started. At that moment, also an initial laser scan was taken (before lifting). This was done for tracking nail head displacements and mesh deformations. After that, the box was lifted to the inclination of 30 degrees and stopped for the first laser scanning. This process continued in 5 degrees steps until the ultimate inclination of the setup was reached (85 degrees) or until the whole system or one of its elements broke. Each experiment was documented and recorded with high resolution cameras.

The test setup and its procedure were more precisely described in Cała et al, 2013.

Figure 5. Test setup during the experiment no. 12 (TECCO® G65/4 mesh, P66 spike plate, 3.5 x 3.5 m soil nail pattern, round gravel)

3.3 Instrumentation and measurements

During each experiment the inclination was measured constantly with an electronic inclination sensor and a manual goniometer. The data from all instruments used during experiments were collected and computerized with Spider 8 which is a the data acquisition device produced by the German company HBM. The deformations of the flexible facing systems were measured every 5 degree step by Terradata AG with a pulse laser scanner (Riegl VZ-400). The horizontal and vertical angular resolution of the laser scanner was set to 0.02 degrees, resulting in a density of $2 \cdot 10^4$ points/m^2 at 20 m distance and 10^4 points/m^2 at 30 m distance and the accuracy of measurement of 7 and 10 mm, respectively.

3.4 Analysis of deformations

Within each experiment the laser scan point cloud was analyzed and one representative cross section for all experiments was chosen. The cross section A (Figure 6 and 7) is located at a distance of 2 m from the lower border of the box and for most of the experiments it corresponds to the section with the highest deformation values. Nevertheless, for some experiments the highest values of deformations occurred in another position. The deformation fields were numbered from one to five starting from the upper left side (Figure 6 and 7) and the place of maximum deformations are shown in Table 2. The scale of deformations is represented by colors with respect to the reference level at 0 degree (light green color). In this regard, colors form yellow to red represent increasing deformations and colors from dark green to dark blue represent decreasing soil depth. In the experimental setup, where the volume of the soil is constant, deformations are balanced with the subsidence of the same amount of the soil.

4. RESULTS AND DISCUSSION

A total of ten experiments were compared in order to show the difference in deformations within flexible facing systems. Figures 6 and 7 show examples of measured deformations at an inclination of 60 degrees with the same configuration of the flexible facing system (G65/4 mesh, P33 spike plate and 3.5 x 3.5 m nail pattern) in round gravel and gravel with silt, respectively. Each experiment was conducted in the same way according to the procedure described in section 3.1. It is apparent that the behavior of two various soils was different. For instance, the round gravel created smooth and symmetrical deformations (Figure 6), while in case of the gravel with silt deformations were irregular and the surface was uneven (Figure 7).

Table 3. Results of compared experiments. Deformations depend on the used mesh, spike plate, nail pattern and the soil type.

Soil friction angle	Nail pattern	Plate type	Wire diameter of the mesh [mm]	Deformation at 60 degrees [m]	Place of maximum deformation at 60 degrees (Figure 6 and 7)	Failure inclination	Experiment number
Round gravel 33 [deg.]	3.0m x 3.0m	P 33	2	0.53*	4	57	21
			3	0.45	4	73	20
Gravel with silt 38 [deg.]			2	0.44	4	63	19
			3	0.40	3	84	18
	3.5m x 3.5m		3	0.45	5	80	11
			4	0.42	4	83	13
Round gravel 33 [deg.]			3	0.65	4	73	9
			4	0.55	5	83	10
		P 66	3	0.52	4	>85	14
			4	0.48	4	>85	12

*Deformation reported at 55 degree box inclination

This also shows that the soil strength has an influence on the first movements of the soil, which for gravel with silt occurred at 5 to 10 degrees higher inclinations than for round gravel.

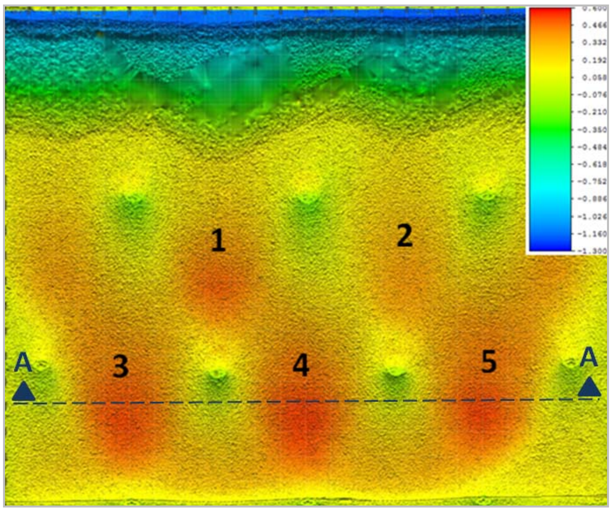

Figure 6. Deformations of the flexible facing system according to the laser scanning. Experiment 10: High-tensile steel wire mesh G65/4, P33 spike plate, nail pattern 3.5 x 3.5 m and round gravel. The cross section A represents the profile for comparison of deformations among all experiments. Numbers on the figure represent deformation fields.

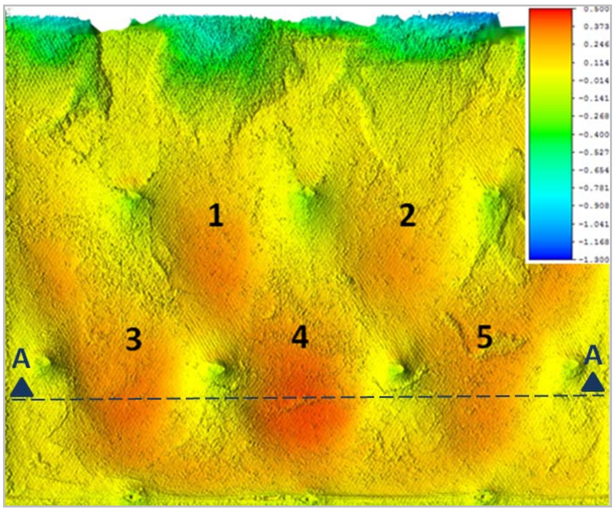

Figure 7. Deformations of the flexible facing system according to the laser scanning. Experiment 13: High-tensile steel wire mesh G65/4, P33 spike plate, nail pattern 3.5 x 3.5 m and gravel with silt. The cross section A represents the profile for comparison of deformations among all experiments. Numbers on the figure represent deformation fields.

In order to quantitatively compare deformations between the experiments, the values of maximum deformation at the inclination of 60 degrees were used (Table 3). Therefore the deformation values were measured from the laser scan data in the cross section A. In most experiments deformations occurred in the middle field (no. 4), but sometimes, like in experiments 10, 11 and 18 the biggest deformations occurred in one of the side fields (no. 3 and 5). However, the difference in deformations between the middle and side sections in a particular experiment was never greater than 0.02 m.

To make the comparison more distinct, experiments were arranged in groups where only one variable was changing (soil type, nail pattern, wire diameter of the mesh or plate type). Table 3 presents the results of deformations and the place of their occurrence at an inclination of 60 degrees within experiments with 2, 3 and 4 mm wire diameter meshes. The failure inclination data presented in Table 2 is the inclination of the box at which the failure of the flexible facing system occurred and the soil material slipped out of the box. The maximum box inclination of 85 degrees was reached without any failure of the flexible facing system in experiments using 3mm and 4mm meshes with the P66 spike plate (Exp. 12 and 14).

Experiments 18, 19, 20 and 21 were conducted in round gravel and gravel with silt conditions using 2 mm and 3 mm wire mesh, the P33 spike plate and nail pattern of 3.0 x 3.0 m. Among these experiments the influence of wire diameter and soil conditions on the deformations was checked. In experiments with gravel with silt (Exp. 18 and 19) the deformation for the 3 mm wire mesh is 0.04m less than for the 2 mm mesh. The same meshes tested within round gravel conditions (Exp. 20 and 21) showed the 3 mm mesh to have deformations of 0.08m less than the 2 mm mesh. Note that in experiment 21 the deformation was measured at the inclination of 55 degrees, which was the last measured step before the flexible facing system failed. Within these experiments it is visible that deformations of the system depend directly on the wire diameter suggesting mesh strength is very important. Stronger, larger diameter high-tensile wire has less deformation and provides better load transfer. Furthermore, it can be observed that within this set of experiments the change of the soil type influences the system deformation as well. Comparing such conditions the differences in deformations equal 0.09m for 2 mm wire mesh (Exp. 19 and 21) and 0.05m 3mm wire mesh (Exp. 18 and 20).

Similar trends of system deformation relative to mesh strength and soil parameters were observed when comparing experiments 9, 10, 11 and 13 in round gravel and gravel with silt conditions using the same P33 spike plate, 3 mm and 4 mm wire mesh and wider nail pattern 3.5 x 3.5 m. In experiments with gravel with silt the deformation is 0.03 m less for 4 mm than for 3 mm wire mesh (Exp. 13 and 11). It is even more dramatic in round gravel conditions being 0.10 m less for 4 mm wire mesh in comparison with 3 mm mesh (Exp. 10 and 9). This may be again concluded that stronger mesh can prevent more deformations. As it was shown in previous paragraph the soil strength has also an influence on the deformations.

Comparing the differences in deformations of the same mesh in changing soil conditions gives the values of 0.20m for 3mm wire mesh (Exp. 9 and 11) and 0.13m for 4mm wire mesh (Exp. 10 and 13).

Experiments 9, 10, 12 and 14 were performed in round gravel conditions using 3 mm and 4 mm wire mesh and nail pattern 3.5 x 3.5 m. In this case the experimental variable is represented by two different spike plates (P33 and P66) which have significant influence on the puncturing resistance and stiffness of flexible facing systems (Table 1) and therefore also on deformations. The difference in system deformation between the experiments using the 3mm and 4mm diameter wire mesh while using P33 spike plate is 0.10m (Exp. 9 and 10) and 0.04m using the P66 spike plate (Exp. 12 and 14). Also these experiments show that stronger mesh more effectively reduces the deformation.

The differences in deformations when comparing experiments with the same mesh but with the different types of spike plates, P33 versus P66, also illustrate the importance of the load transfer between the mesh and the spike plate. The results give 0.13m less deformation with the P66 spike plate in the case of 3mm diameter mesh (Exp. 9 and 14) and 0.07m less deformation in case of mesh made of 4mm wire (Exp. 10 and 12). This again illustrates that stronger wire at the spike plate transfers load better to the soil nails as the deformation is nearly half with the 4 mm facing compared to the 3 mm.

The influence of the nail spacing on the flexible facing deformations is also significant. Experiments 9, 11, 18 and 20 were conducted in round gravel and gravel with silt conditions all using 3 mm diameter wire mesh and P33 spike plates. The change of nail spacing from 3.5 x 3.5 m to 3.0 x 3.0 m resulted in reduction of the deformations of the mesh. The difference in deformations in gravel with silt conditions is 0.05 m less at a 3.0 m nail spacing (Exp. 11 and 18) while in round gravel conditions (Exp. 9 and 20) the difference is already 0.20 m.

The extreme difference of deformations recorded within all experiments had the value of 0.25m. The biggest deformation of 0.65m occurred in experiment 9 performed in round gravel conditions with 3mm diameter mesh, P33 spike plate and 3.5 x 3.5 m nail spacing. While the smallest deformations occurred in experiment 18 performed with the same mesh and the same spike but with gravel with silt and 3.0 x 3.0 m nail spacing. It is clearly visible that soil conditions and even more nail spacing have great influence on the deformations. Together with increasing the soil strength or/and decreasing the nail spacing the deformations decrease as well. In conditions of the same soil and nail spacing the biggest influence on deformations are spike plates and even more so the wire diameter, therefore strength, of applied high-tensile steel mesh.

5. CONCLUSIONS

The slope stabilization systems using high-tensile strength mesh in combination with soil nails may be used in various conditions where high resistance and low deformations are required. The presented results show the relationship between the deformations and the nail pattern, soil, mesh, and spike plates. All these variables have influence on the behavior of the flexible facing systems and in this contribution are quantified in terms of deformation as a function of inclination. The maximum deformations for the tested combination of variables range between 0.40 m and 0.65 m. These results represent important information for the characterization of the stiffness and maximum strength of the flexible facing systems. This paper shows that increasing wire strength of the flexible facing systems by using the high-tensile strength steel and of various wire diameter in combination with optimized spike plates it is possible to provide integrated force transfer and stabilize steeper slopes or decrease deformations. This knowledge gives designers and engineers great room for optimization of the design in order to meet specific requirements and to evaluate the cost of various installation options.

REFERENCES

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., Rist A., Baraniak P., Roduner A. 2013. *Large scale field tests for slope stabilizations made with flexible facings.* Proceedings of Eurock 2013. Wrocław, Poland 23-26 September 2013:659-662

Phear, A., Dew, C., Ozsoy B., Wharmy N.J., Judge, J., Barley, A.D., 2005. *Soil nailing – best practice guidance.* CIRIA C637.

EN 14490:2010 Execution of special geotechnical works. Soil nailing.