Geogrid Reinforced Steep Slopes and Retaining Walls Prediction and Field Monitoring of Geogrid-Strains and Earth Pressure on the Facing System

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ABSTRACT: These days geogrid reinforced earth structures are installed in considerable heights and have become very popular and economic structures. The facing systems used can vary not only in terms of the style and finish but also in the technical requirements. Special attention has to be paid to the compound (soil-geogrid) mechanism and interactions. For the design the European harmonized standards as well as national guidelines or recommendations like BS8006 (UK) and EBGEO (German) have to be followed. EBGEO allows for a reduction of the lateral stress in comparison to active earth pressure in some cases. This leads to an economic but safe design. Based on literature and exemplarily shown on two case studies the lateral stress on the facing system will be shown in detail as well as the stress-strain distribution on a geogrid during installation and construction for verification of the chosen design concepts.

1 INTRODUCTION

These days geosynthetic reinforced soil structures belong to the most economically attractive construction methods due to their flexibility and versatility. Also under the ecological point of view, as e.g. CO_2 reduction, further positive impulses for this type of application can be expected in future.

DIN EN 14475, the British design code BS8006 as well as the German design recommendations EBGEO 2010 are state-of-the-art standards in order to safeguard the constructions.

Special attention has to be paid to the design of the facing, as these elements are directly exposed to the environment and deformations of the construction can be seen immediately. The mentioned design codes do not give a unique calculation of lateral stress acting on the facing elements. DIN EN 14475 already differentiates between several types of facing elements, depending on the stiffness:

- Rigid facings, e. g. full height panels
- Semi flexible facings, e.g. concrete blocks without rigid connections, gabion baskets
- Flexible facings, e.g. wrap around method

The lateral stress has to be different from the active earth pressure calculated according to Rankine´s theory due to the geosynthetic reinforcing elements, nailing the fictive failure zone.

As this becomes a hyper static system, the earth pressure distribution on the facing is indifferent.

Nevertheless, the design has to be proper and worked out on the safe side, so additional information has to be gained from sites and large scale tests.

2 CURRENT DEVELOPMENT

2.1 *Lateral stress on facing*

Pachomow et al. (2007) collected several test-field data of executed walls in heights between 2.0 m and up to 30 m, with information concerning the lateral pressure on the facing given.

It is interesting that the lateral stress gained by self-weight of the construction remained within a range of up to 50 kPa (fig. 1), although significant higher values would have been expected especially for high walls. The data indicate that the height might not have a decisive influence at all.

Normalising the height of all test field data, and recognising that nearly all data are linked to non-cohesive soils as well as to slope inclinations between 70° and 90°, the relationship between the vertical and lateral stress can be compared to the active earth pressure coefficient, being expected in the range of 0.2 and 0.35, depending on the theory and boundary conditions. A significant reduction of the lateral stress in comparison to the vertical stress has to be stated for 60 % of the wall height, figure 2.

The data can be separated for different front-wall systems, showing a clear tendency to higher lateral stress at higher front wall stiffness.

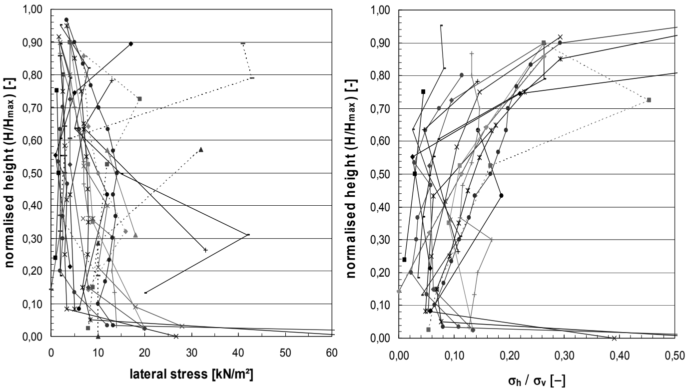


Figure 1 and Figure 2: Lateral stress on facings and relation of σ_h/σ_v from full-scale tests, drawn against normalised height of the constructions, Pachomow et al. (2007).

2.2 *Deformation of facings*

Based on full scale tests varying the type of reinforcement by using several commonly known products, beside the stiffness of the facing a clear tendency can be obtained concerning the stiffness, described by the secant modulus J of the products:

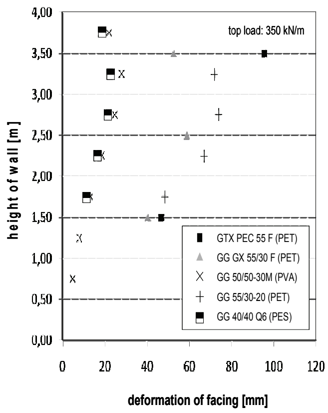
$$J\ [kN/m] = \text{strength } F\ [kN/m]\ /\text{strain } \varepsilon\ [\%] \qquad (1)$$

Although the products have been charged in a small range of nominal strength varying from 40 kN/m up to 55 kN/m, the secant modulus can be seen to have a significant influence on the deformation of the wall facing. Figure 3 shows preliminary results of a 4.0 m high construction using a weak facing system and a load beam 1.0 m behind the wall surface, applying a top load of up to 350 kPa. The deformation varies significantly depending on the type of product. All products performed satisfactory in an acceptable range, while some products allow for higher loads and show an enhanced performance in terms of serviceability.

3 EUROPEAN DESIGN CODES

Exemplarily the mostly used design codes in Europe, BS 8006 and EBGEO 2010, dealing with reinforced earth will be discussed in the following.

Following the basic principles as described in 2.1, EBGEO allows for a reduction of the lateral stress as compared to the Rankine´s active earth pressure. The well known coefficient for the lateral active earth pressure kak is just used as basic parameter (eq. 2), taking the inclination of the wall as well as the soil parameters (e.g. angle of internal friction φ´) into consideration. The correction factor ηG as per Figure 4 is then applied, knowing well, that using the lateral active earth pressure ka as basic parameter is just an interim solution up to full understanding and modelling of reinforced earth. In the upper part of the construction respectively on the actual construction level, the earth pressure due to compaction (not shown in figure 4) becomes decisive, but is going to be superposed by the earth pressure resulting from the self-weight of the construction as per figure 4.



	Correction Factor		
	η_g		η_q
	0 < h ≤ 0.4 H	0.4 H < h ≤ H	
rigid	1.0	1.0	1.0
semi flexible	1.0	0.7	1.0
flexible	1.0	0.5	1.0

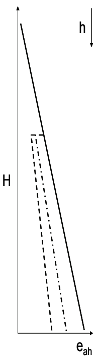


Figure 3: Deformation of full scale walls with semi-flexible facing, depending on the product used (Pachomow & Herold, 2009).

Figure 4: Correction factors applied to k_{ah} according to EBGEO, 2010.

$$E_{Facing} = (\eta_g * ka_{gh,k} * \gamma_k * H_i * \gamma_G + \eta_q * k_{aqh,k} * q * \gamma_Q) * l_v \qquad (2)$$

with

E_{Facing}	Earth pressure on facing element [kN/m]
η_g, η_q	Matching coefficient [-]
$k_{agh,k}$, $k_{aqh,k}$	Coefficient active earth pressure [-]
γ_k	Weight per unit area of the soil [kN/m³]
H_i	Covering [m]
q	Traffic load [kN/m²]
γ_G, γ_Q	Partial safety factor DIN 1054 [-]
l_v	Vertical space between layers [m]

In opposition to EBGEO, the earth pressure following BS 8006 is calculated using the active earth pressure coefficient k_{ah} for the structure, superimposed by k_0 in the upper part. The reduced stress acting on the front of the construction depending on the stiffness of the wall-facings is considered by a reduction of the connection stress, e.g. by 25 % in the upper 60 % of wall height using wrap-around method.

The BS 8006 concept results in having the highest connection stress requirements at the footing of the construction, while research and lessons learned from failures indicate to have the highest stress levels at approx. 1/3 height starting from the bottom of the walls.

Nevertheless, the reduction of the lateral earth pressure has a direct influence on the design of reinforced walls and allows for steep walls with a friction connection between e.g. blocks and reinforcement. This becomes decisive as the costs of the facing and connection mode significantly influence the costs of the total construction, while the costs of the product used are not of the significant range. By using high strength products and an economic but high quality facing system, the performance of geosynthetic reinforced structures can be increased and optimised, figure 5.

Figure 5: Block wall with friction connection under construction, Zanovica (SK), 2009.

4 EVALUATION OF DESIGN BY FIELD MEASUREMENTS

4.1 *Noise protection wall with lime stabilised soil (Bammental, Germany)*

Vollmert at al. (2010) reported on strain measurements and back-calculations of forces on the facing of a 12 m high noise protection barrier wall, designed according to the principles of EBGEO 2010. As a result of its hillside situation the total height of the construction is partly more than 18 m with an inclination of the facing of 70°, fig. 6.
During the profiling of the construction site of the residential area a large quantity of soil has been excavated. This should be used as building material for the earth wall. The in-situ soil was mixed with binders (lime-cement-stabilization) on site, transported to the installation location and installed by compacting layers. The facing of the geosynthetic reinforced soil structure consists of welded, specially aluminium galvanized steel wire grid mats (rectangular, openings 100 mm x 100 mm). A corresponding erosion control mat made of a synthetic monofilament is used in front of the elements.

Geogrids with a high extensional stiffness are used as reinforcing elements. For economic reasons and to improve the reliability of the construction (danger of confusion in the case of a similar visual appearance of the product) only two geogrid types, in this case Secugrid® 200/40 R6 and Secugrid® 40/40 Q6, are installed. The design strength according to EBGEO, taking creep, installation damage, pH = 12.5 and a partial factor of safety for the material of 1.4 into consideration, is given to 87.3 kN/m resp. 17.5 kN/m².

The connection between front elements and geogrids is carried out - corresponding to the static verification - only via friction.

The measurement concept which has been established allows for a determination of the horizontal stress affecting the facing by means of an instrumentation of the steel grid element. Furthermore, it is necessary to carry out earth pressure measurements in order to be able to register the influence and the effect of the formation of restraints and arches (see Pachomow et al. 2007) between two reinforcement layers as well as the vertical strains and thus the load distribution in the front area.

For the realization of this measurement concept the following detectors are used:

- Earth pressure cell (Glötzl)
- Strain gauge (HBM)
- Temperature sensor

The settlement and deformation measurements which have been carried out show:

- Settlements in the soil body already occurred during the construction phase with values of predominantly < 1 cm per layer. The settlements could be balanced already during the construction process by means of corresponding corrections.
- In analogy to the vertical deformations only very low horizontal deformations could be detected, which were within the measuring tolerance and which did not increase with the rising installation height.
- The settlements in the subsoil were clearly below 30 cm.
- At the end of December 2008 only just minimum settlements in the range of millimetres were detected. It can be assumed that the decisive settlements have been subsided.
- The strains in the geogrid near the front are very low (figure 7) and remain nearly constant.

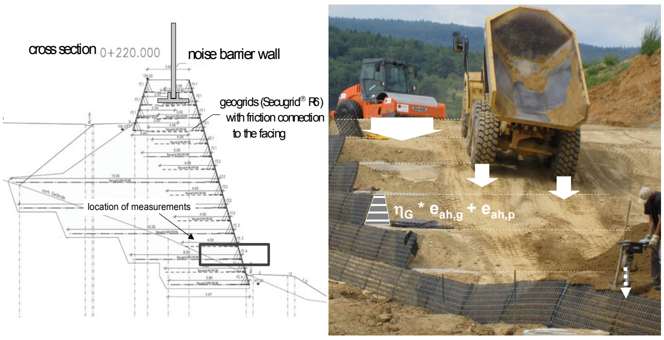


Figure 6: Cross section and installation stress on facing. Noise barrier wall, design according to EBGEO 2010, Bammental, Germany

Within the framework of the preliminary evaluation of the results the measured earth pressures were checked as to their plausibility. The values which were obtained directly after installation were verified with the values after the first covering and construction levels. Compared to the expected values the test values show qualitatively as well as quantitatively a good correlation - without any further corrections. Especially noticeable are:

- the very low horizontal stress of less than 5 kPa in the front earth pressure cell
- the tendency to unitize the vertical stresses.

Besides the very low total level of the operational stress of the geosynthetics also the good correlation of the back-calculated medium force within the geogrid of approx. 3.5 kN/m with the horizontal stress of 5 kN/m measured in the first stress gauge is noticeable.

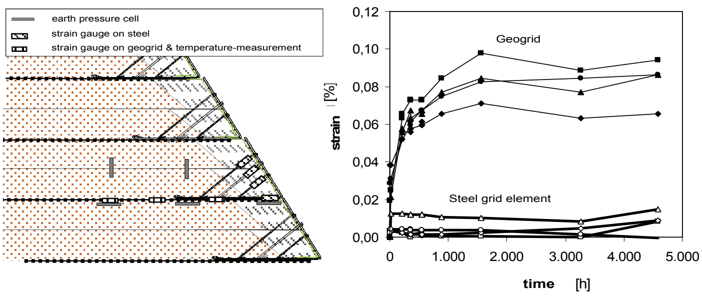


Figure 7: Detail for measurement application and strains versus time.

4.2 *Steep wall with steel mesh facing (Valdecaňas, Spain)*

The island "Valdecaňas" is located in the middle of a 7,200-hectare water reservoir at the foot of an imposing mountain range, the Sierra de Gredos in Spain, approx. 160 km south-west of Madrid. The island is developed as tourism resort, which consists of a golf resort, sailboat marina, holiday village, villas, sports complex and a congress centre.

In the area of a planned access road, located in the north-eastern part of the island, it was required to fill up the island up to 21 m high. To create as much space as possible for construction on top of the created plateau, the slope sections needed to be built as steep as possible.

Conventional concrete retaining walls as slope stabilisation measure were no option as they would not create an attractive impression from a landscaping point of view. As economic and ecologic alternative solution it was decided to construct the slopes as 70° inclined steep geogrid reinforced earth structure. The facing of the reinforced embankment was built using the so called "wrap around method" in combination with steel mesh facing elements, which were used as formwork during the installation and compaction of the fill soil.

To be able to analyse the realistic stresses developed in the constructed reinforced slope and to compare those to the stresses determined in the design, a monitoring programme was carried out using strain gauges, where DMS were applied to a selected geogrid layer in the lower part of the reinforced soil structure. In figure 8 a typical cross section of the geogrid reinforced embankment is shown as well as the location of the monitored geogrid together with the applied strain gauges.

The strain measurements started immediately after installation of the geogrid and will be continued to cover a period of approx. 2 years. Currently a period of approx. 9 months is covered, whereby the embankment in the monitored area was completed in a period of approx. 5 months. In figure 8 also the strain development across the embedment length of the monitored geogrid is shown.

The results show clearly that the largest deformations have taken place during the construction process of the reinforced earth structure. The development of the measured strains across the monitored geogrid also shows that the peak strain is developing near the facing and decreases with increasing embedment length. This indicates that the line of maximum tension inside the reinforced earth structure is close to the surface.

Following the FE-analysis worked out for the serviceability limit state taking construction steps into consideration, the maximum strain would have been achieved at 3.0 m behind the facing, so the measurements fit quite well with the prediction.

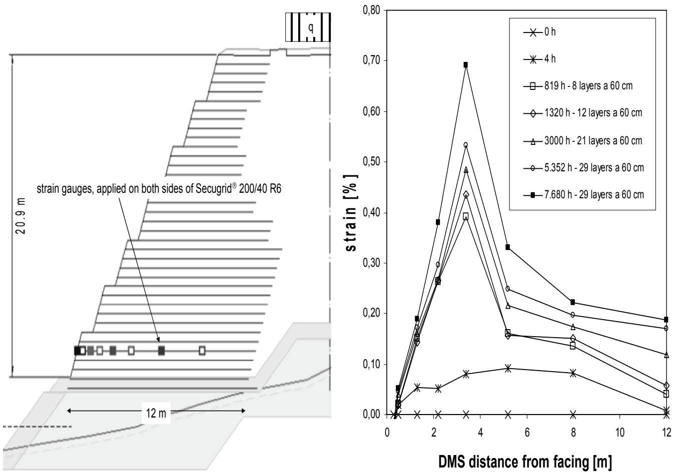


Figure 8: Cross section of steep slope Valdecaňas and results of strain measurements. Steep embankment, design according to BS 8006, Sierra de Gredos, Spain.

5 CONCLUSIONS AND FINAL REMARKS

European regulations give complete rules how to handle and to design geosynthetic-reinforced walls and slopes. The most commonly used standards BS 8006 and EBGEO are significantly different, not only for the partial safety factors but as well for the design rules as e.g. for the earth pressure on facings and connections. Due to this a clear decision has to be made for each project what standard has to be used and has to be combined with the national standards for the safety concept in geotechnical works.

EBGEO gives a clear line in accordance with DIN EN 14475 and DIN 1054:2005, linked to EC-7. Several new design procedures are given in the actual edition 2010. Nevertheless, both standards show approx. comparable results of quantities of required reinforcements with some differences in details.

Executed large scale tests as well as site measurements indicate that the design is by far on the safe side. Special attention has to be paid to the facing system. Current development shows, that friction connection can be a proper and economic solution, while the serviceability can be increased by using welded geogrids with high secant stiffness (figure 3, figure 9).

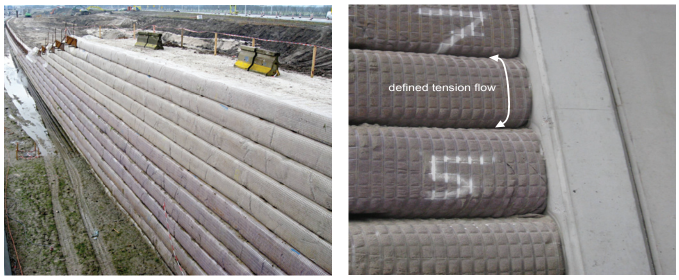


Figure 9: High serviceability and limited deformation on a wall with wrap around method using geogrids with flexural rigidity and high secant modulus.

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