Improvement of Soil Properties, Bratislava on June 4 – 5, 2007

Improving the Bearing Capacity of Soils with Geosynthetics

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ABSTRACT: Due to the globalization of the world economy and the global increase of trade, there is an increasing shipment of goods, which creates high demands on the maintenance and development of an efficient infrastructure (roads, railways and waterways). The development of infrastructural projects will be a booming sector of the construction industry around the world with the highest demands in Asia and Europe. Sustainability concepts for the construction activities and funding problems of the contracting authorities are current boundary conditions which can be accommodated optimally with geosynthetic construction methods. At the same time, besides the technical advantages, economical and ecological advantages can be used too – saving construction costs and taking care of building material resources. This paper will provide a state-of-the-art report about international infrastructural projects.

1. General

Soil alone is able to carry only compressive and shear forces. However, through the use of geosynthetics as reinforcing elements, soil structures can be built to carry tensile forces.

It's a actual vision that the reinforcement of soil with geogrids will be as common in the future as the reinforcement of concrete with steel mesh is today.

Today, it is already state-of-the-art for earthworks or base courses in road works or railway projects to be reinforced with geosynthetics. Like reinforced concrete, the technical properties of soil can also be considerably improved in combination with geosynthetics, as geosynthetic reinforcement materials will absorb tensile forces. The aforementioned advantages provided by geosynthetic-reinforced structures are meeting with increasing acceptance the world over, and this trend is further supported by their excellent track record regarding, e.g., seismic loading. Irrespective of normal traffic load and stress in normal usage, under sudden seismic stress, the original short-term strength of geosythetic reinforcement products comes into its own to provide a valuable source of working load reserves in the case of a catastrophe.

In road or railway applications the insertion of horizontal geogrid layers in granular base courses provides an increased modulus, hence a lateral confinement to the system.

Fig. 1 demonstrates the lateral confinement of the soil particles by the weight of a car resting on the geogrid-reinforced gravel columns. This lateral confinement resists the tendency for base courses to create large deformations (rutting) under the anticipated dynamic loads.

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Fig. 1. Geogrid reinforced gravel columns carrying a car

This reinforcing effect will also lead to the longer service life of traffic structures, but it's very difficult to show this improvement by a simple plate loading test. More research is still needed and necessary. In addition, geogrid reinforced traffic areas can avoid massive soil exchanges by improving the in situ (existing) soil with the reinforcement.

Geogrid-reinforced soil structures as a flexible alternative to conventional construction methods, e.g., concrete retaining walls, also allow for the preparation of land for building even under difficult topographic conditions. Geogrid-reinforced steep slopes enable the development of land for building on a limited space, which is extremely beneficial in the case of expensive land prices. From an economical viewpoint, a reduction in the overall construction costs of at least 30 % can be achieved compared to conventional methods.

The current design procedure for appropriate constructions is based on classical soil mechanics and, up to now, has not adequately taken the visco-elastic properties of geosynthetic reinforcement materials and the effects of geosynthetic/soil composites or geosynthetic soil interaction into account. But it has been proven that the present design procedure for reinforced earth constructions comprises quite considerable and reassuring safety reserves, which also contribute in furthering the acceptance of such structures. Fig. 2 shows a highway bypass section which was in service with full highway traffic for several years, when the final bearing capacity of the geosynthetic reinforced structure should be evaluated. For loading the structure, a big counterpressure rig was installed on the top level of the structure, and the reaction forces were taken by big steel reinforced anchor piles. Reaching more than 20 times the calculated design load of the geogrid reinforced structure, the anchor piles failed, but the geogrid-reinforced structure did not even move (Bräu & Floss, 2000).

Optimized design procedures and the improved utilization of geosynthetic reinforcement products will distinctly increase the economic benefits of this method of construction even more. Increased research work on this issue is desirable, particularly in the interest of public building authorities. Constructing steeper cut and fill sections, bridge abutments and noise protection walls, frequently in conjunction with smaller areas and/or less land acquisition, should be consistently made use of as options well in line with even tighter public budgets.

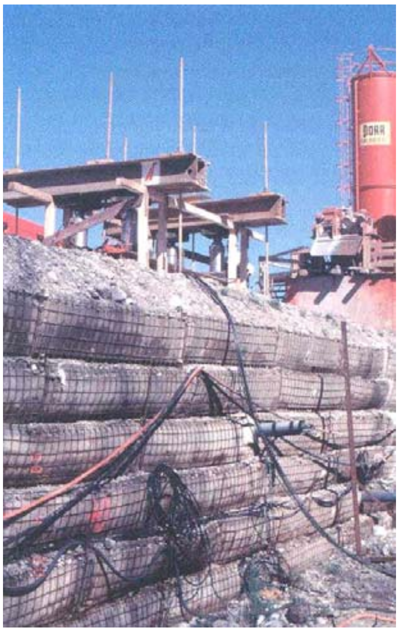


Fig. 2. Testing the bearing capacity of a geogrid-reinforced soil structure

2. Actual design practice and future needs

When designing the reinforcement of bad bearing or soft soil layers under traffic areas, a "membrane theory" approach is normally taken. Based on our own experience in the design of unpaved access roads, the design approach of Giroud & Noiray (1981) can be recommended when product-specific aspects of the geogrid are also considered. For unpaved access roads, comparatively large deformations are accepted, and the "membrane theory" is more relevant.

In contrast, the "membrane theory" is not adequate for paved roads where only very small deformations are acceptable shown and Fig. 1 clearly demonstrates that the bearing improvement of gravel columns ,cannot be described by any "membrane theory" approach! An empirical design approach based on many years of application experience is included in a design disc available for welded Secugrid® geogrids (Fig. 3).

Fig. 3. Design disc for bearing layer reinforcement in traffic areas
using welded Secugrid® geogrids

By introducing the CBR value of the subsoil and defining the CBR value at the surface of the bearing layer, a reduction in the thickness of gravel or crushed stone layers may be estimated using the design disc. Sometimes a second reinforcing layer is recommended, and for CBR < 2 % , a special, more detailed, design approach is necessary.

By designing a geogrid-reinforced soil structure, the actual design strength $F_{Bi,d}$ of a geo-synthetic reinforcing element is defined as follows according to EBGEO (1997):

$F_{Bi,d}$ = $F_{Bi,k0} / (\gamma_B \cdot A_1 \cdot A_2 \cdot A_3 \cdot A_4)$

$F_{Bi,k0}$ = characteristic tensile strength (short-term strength, laboratory value)

γ_B = general safety factor (only EBGEO)

A_1 = factor for creep (for static loads: $A_1 \geq 5$ for PP, ≥ 2.5 for PES or proof with creep tests)

A_2 = factor for damage due to transportation, installation and compaction (fine grained soils: $A_2 \geq 1.5$, coarse mixed grained soils $A_2 \geq 2$ or field tests)

A_3 = factors for connections, overlaps, joints, etc. (no overlaps in direction of stress: $A_3 = 1.0$)

A_4 = factor for weathering (UV), chemical and biological degradation

For the given example for a welded geogrid produced of polyester resin material, the following partial safety factors are determined:

A_1 = 1.53
A_2 = 1.02
A_3 = 1.0
A_4 = 1.1

Combining these partial safety factors with the general safety factor $\gamma_B = 1.3$, the short-term strength of 80 kN/m of the product is reduced to a design strength of only 33.7 kN/m or 42 % of the short-term strength.

All the data to establish the A_1 to A_4 partial safety factors are estimated and calculated by laboratory tests at breaking load conditions of the geogrid and testing in air instead of testing under soil confinement conditions. At a breaking load the reinforcing products show elongation values of $\varepsilon >> 5$ %, whereas the serviceability of the reinforced earth structures is limited to deformations of $\varepsilon < 2$ %. Several in situ measurements in reinforced earth structures even document that the elongation of the reinforcing geogrids is even less with $\varepsilon < 0.5$ % (Pachomow, *et al.*, 2007). Even while being confident that the actual design practice of geogrid-reinforced earth structures is a very safe approach, a lot of future research is needed to fully understand and describe the geogrid/soil interaction as a composite material structure.

The very high bearing capacity of geogrid-reinforced soil structures cannot merely be explained by the friction interaction of the soil and reinforcing elements, but additional interlocking effects with forces mobilized in front of the cross bars have to be considered.

In a special research program at the RWTH Aachen (University of Technology, Germany), the effect of geogrid cross bars has been studied. Fig. 4 shows the mobilisation of drag forces as friction and soil resistance in front of the cross bars (Ziegler *et al.*, 2007).

In grids with more than one cross bar, the rear cross bars cause a slighter degreed of drag force leaps than the ones in the front as the continuous strain of the grid diminishes the displacement of the cross bars. Thus, the cross bars' loads decrease continuously in the rear area (Fig. 4).

This effect, which is not considered by the common design procedure, continues up to the point x_0 from which on the grid it is no longer subject to significant displacement since no more loads are transferred by the cross bars. Not taking any safety factors into consideration, the distance from the place of pull-out force induction to the point x_0 equals the required anchor length of the reinforcement.

Based on this approach it is also possible to deal with actual loads to the geogrid junctions. The ladder-shaped drag force line also clearly shows that the maximum stress at the junctions can only correspond to the first drag force leap. It is obvious that this drag force leap ΔZ_1, particularly with a full grid, is much lower than the force Z_3 introduced at the start of the grid.

An upper estimate for the stress at the junction results when one calculates the drag force difference between a corresponding pull-out test with pulling out the longitudinal bars only (test with no cross bars) and a pull-out test with only one cross bar. This difference in pull-out force has to be transmitted in the junctions of the sample. In a real grid, however, the stress at the junction would be even smaller, since the mobilised area is restricted by the subsequent cross bar.

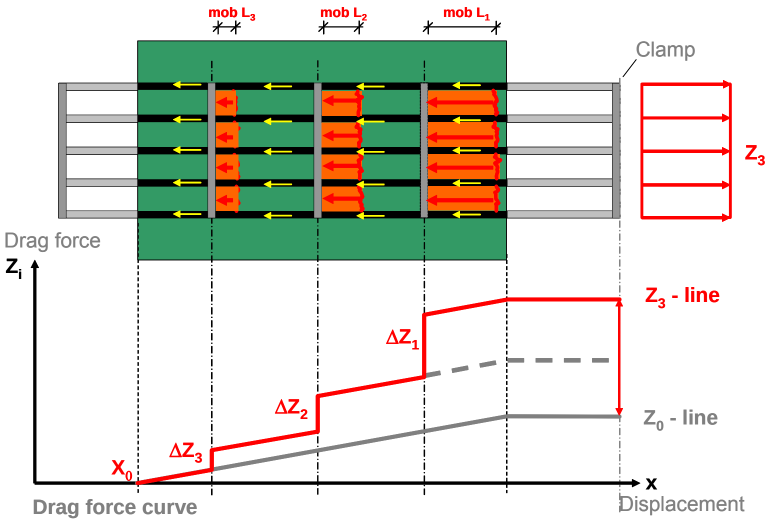


Fig. 4. Mobilisation of friction and soil resistance by the pull-out of a geogrid

In order make full use of the soil/geogrid interaction, the junctions of a geogrid have to transmit forces from the cross bars, to length bars and the junctions have to be strong enough to carry the ΔZ forces as shown in Fig. 4. A different junction design of geogrid products as shown in Fig. 5 will clearly show different soil/geogrid interaction behaviour.

The latest research studying the load transfer mechanism by soil/geogrid interaction with "in soil" testing using a test setup with a movable front wall and introducing forces from the soil into the reinforcing geogrids show the future guiding results (Bussert 2006). Fig. 6 shows the test setup.

The test results show that the interaction of the soil and geogrid mainly depends on the geosynthetic layer spacing, soil grain size, and the geosynthetic aperture size as well as the strength of the shape and extensional stiffness of the geogrid product. Contrary to the presently used design methods, no correlation between the geosynthetic tensile strength and serviceability of the geosynthetic reinforced soil structure can be accomplished. The stress reduction at the front wall by moving the front wall in the x-direction (Fig. 6) caused by different geogrid products and with no reinforcement is shown in Fig. 7. With "stiff", welded and extruded geogrids, a reduction of the stress level is already given before any front wall movement is initiated. A reinforcing effect occurs immediately without any deformation of the front wall, whereas the "textile-style" woven geogrids need an initial deformation to activate the reinforcing effect. When fully activated, the soil/geogrid composite material is characterised by a significantly smaller degree of effective horizontal stress than the unreinforced soil.

This current report on recent research results shows the promising development of a better understanding of soil/geogrid interaction for the design of even more effective geogrid-reinforced soil structures.

The following case histories will document the technical, ecological and economical benefit of projects where the use of geosynthetic reinforcement has enabled advantageous solutions compared to conventional construction methods. All the structures are dimensioned and designed based on current, very conservative design approaches.

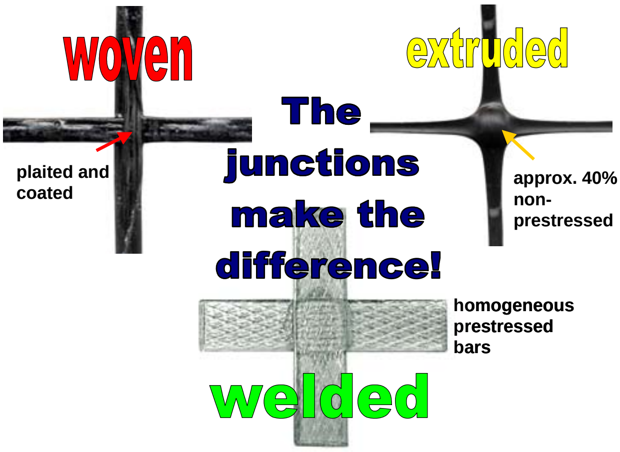


Fig. 5. Different junction design of existing geogrid products

1 side frame
2 base plate
3 load plate with reinforcement
4 threaded rods
5 plug gauge with fine thread
6 force measurement
7 movable front plate
8 HDPE coating with PE membr.
9 displacement transducer
10 sand/gravel
11 geosynthetic layer

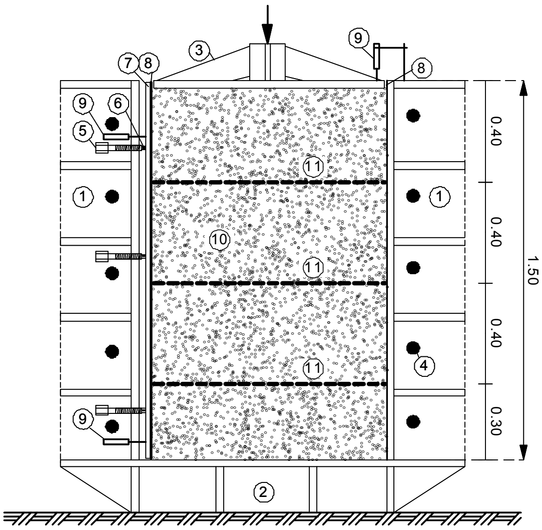


Fig. 6. Test setup with movable front wall (Bussert 2006)

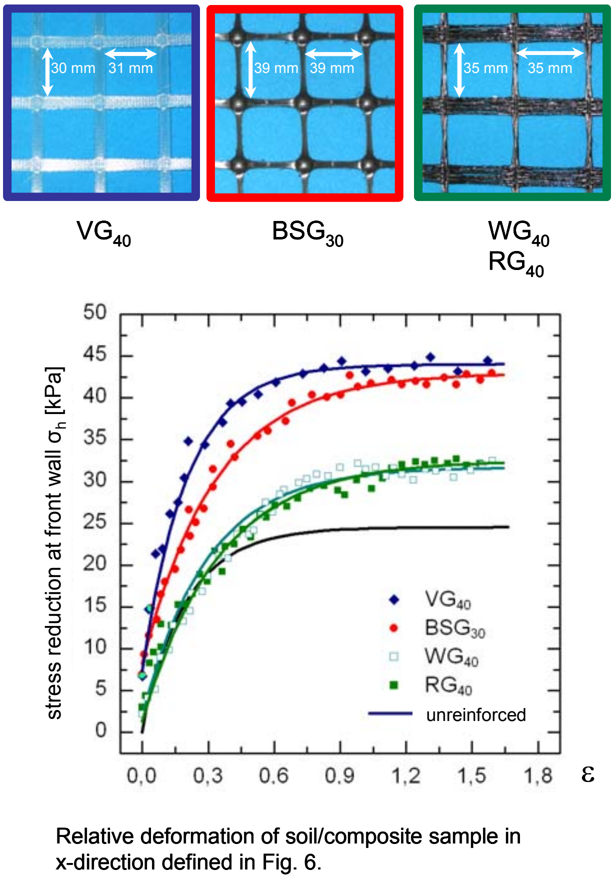


Fig. 7. Earth pressure/stress reduction at movable front wall with different/no reinforcement of the soil body

3. Case histories

3.1 Rehabilitation of Bucharest-Constanta Railway, Romania

The Bucharest - Constanta railway section Bucharest - Constanta is the main railway route in Romania, both for international and national traffic. It links the capital Bucharest to the city of Constanta, which is the main port at the Black Sea as well as the main tourism, entertainment and health resort of Romania. The Bucharest-Constanta line is part of the "Pan-European Corridor IV railway line" connecting Germany and Turkey.

The overall objective of the rehabilitation of the Bucharest - Constanta railway section is the upgrading of the railway line to EU standards. The project refers to an existing double-tracked line, which will be completely rehabilitated with the help of EU-ISPA Programme funding, Romanian Government funds and a loan granted from the Japan Bank for International Cooperation (JBIC). The total railway track is subdivided into three sections and has a total length of approx. 225 km. So far, approximately 1.1 million m^2 of Secugrid® 30/30 Q1 geogrids and approximately 2.2 million m^2 of Secutex® 251 GRK 4 geotextiles have been ordered for Section 1 (Baneasa-Fundulea) and Section 3 (Fetesti-Constanta) to increase the long-term stability of the rehabilitated railway tracks. The decision for Section 2 (Fundulea-Fitesti) is soon to be made. Fig. 8 shows a map of the Romanian railway network.

The existing subgrade in the area of the railway track consisted of a mix of granular soil (old ballast, sand, gravel and stones) and fine grained material (loess). It provided insufficient bearing capacity for the planned railway superstructure. The design of the railway superstructure was technically oriented towards standards defined by the German Federal Railway Authority (EBA). A typical cross section of the Formation Protection Layer (FPL) designed for speeds of >160 km/h is given in Fig. 9.

On top of the FPL (0-63 mm) a static deformation modulus at reloading (according to DIN 18134) of $E_{V2} = 80$ MPa was specified. The project specifications required the use of geogrids with rigid nodes as well as a Certification and Approval by an authorized European Railway Testing Institute. NAUE GmbH & Co. KG, NAUE Romania s.r.l. together with BBG Bauberatung Geokunststoffe GmbH & Co. KG proved to the contractor that the specified properties for the geosynthetic components could be met with the use of Secugrid® 30/30 Q1 geogrids and Secutex® 251 GRK 4 geotextiles. In Fig. 10 the installation of the FPL and the ballast on top of the geotextile Secutex® 251 GRK 4 and the geogrid Secugrid® 30/30 Q1 is shown.

Static and dynamic load plate tests were carried out to determine the deformation modulus E_{V2} & E_{Vd} on top of the formation protection layer and on the existing foundation level. The existing bearing capacity was measured directly on the foundation level with a dynamic load plate test (every 100 m), whereas on top of the FPL, a dynamic deformation modulus E_{Vd} (every 50 m, immediately after installation of FPL) and a static deformation modulus E_{V2} (every 200 m, 5 days after installation of FPL) were measured.

The load plate tests carried out proved that the use of Secugrid® 30/30 Q1 and Secutex® 251 GRK4 underneath the FPL resulted in an additional safety potential for the railway track, as the minimum required project-specific deformation modulus of $E_{V2} = 80$ MPa has been exceeded by more than 60 % of all the load plate tests carried out.

Fig. 8. Romanian Railway Network

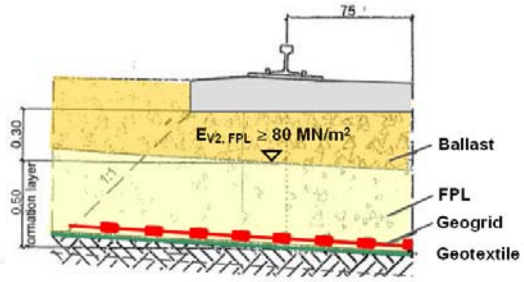


Fig. 9. Standard Cross Section of FPL (Formation Protection Layer)

Fig. 10. Installation of FPL and Ballast on Secutex® 251 GRK 4 and Secugrid® 30/30 Q1

3.2 Oman Polypropylene LLC Plant, Sultanate of Oman

Oman Polypropylene LLC started to build its polypropylene plant at the end of 2004.

For the development of the port at Sohar, which is located at the Gulf of Oman, an area of approximately 24 hectares was artificially created by dredging operations for the port development. The 2,000-hectare Sohar port and industrial zone will house mega industrial facilities ranging from an oil refinery and aluminium smelter to steel mills. The zone will be one of the world's biggest greenfield petrochemical and metal-based industrial hubs.

Oman Polypropylene is integrated with the refinery. The project will add value to Sohar Refinery's propylene stream to produce polypropylene that can be used in an array of downstream industries.

Soil investigations have encountered loose to very soft sand and organic silt layers at a depth of approximately 6 m. It was therefore necessary to increase the bearing capacity of the weak subsoil for the development of access roads and storage areas.

Fig. 11. Oman Polypropylene LLC Plant

Fig. 12. Installation of Secugrid® base course reinforcement

The base course was installed in two layers each of 300 mm of crushed granular material. A base layer and an intermediate layer of Secugrid® 40/40 Q1 ensured an increased modulus of the reinforced granular layers and finally a stable platform for the planned roads and storage areas on the originally soft subsoil. Altogether approximately 150,000 m^2 of Secugrid® 40/40 Q1 were installed in this project.

3.3 Tabing-Duku Road Widening Project, Indonesia

The Tabing-Duku project near the town of Padang on the largest of the Indonesian islands, Sumatra, required an existing road from the airport to the city center to be widened at the most cost-efficient price possible. In spite of extremely problematic ground conditions on the site with low load-bearing capacities and a high ground-water level, NAUE worked out a possible solution in cooperation with BBG Bauberatung Geokunststoffe GmbH & Co. KG. The solution involved an embankment reinforced with uniaxial Secugrid® R geogrids.

Fig. 13. Extreme soil conditions on the site

15,200 m² of Secugrid® 120/40 R1 geogrids made of polypropylene (PP) were installed with anchorage lengths between 6.0 m and 10.0 m. The reinforced slope had an inclination of more than 50° and was constructed with the wrap-around method. The slope surface was finally covered by natural vegetation. The original design envisaged geogrid reinforcement layers with 60 - 80 kN/m tensile strength with a layer spacing of 0.50 m.

However, the limited budget did not allow for the implementation of this version and so the decision fell to Secugrid® 120/40 R1. The selected type of product allowed for the installation with a greater layer spacing because of its higher short-term and long-term tensile strength, which led to greatly reduced installation costs.

The Secugrid® solution with geogrid widths of 4.75 m likewise allowed for faster and more cost-efficient installation, in particular as the loss through overlapping is less compared with narrower products. As the subsoil conditions were extremely adverse and because, in some parts, it was necessary to install Secugrid® "underwater", the bottom layer of the embankment suffered extreme deformation, as it was expected. But the Secugrid® was able to absorb these enormous forces without any problems and without any visible damage. The deformations were remedied as further layers of Secugrid® were installed to reinforce the embankment.

Measurements were taken on the upper edge of the embankment to determine the degree of deformation. Hardly any deformations were noted, which confirmed that Secugrid® had allowed an existing road to be successfully and safely widened on an extremely soft subgrade – at a favourable costs.

Fig. 14. Reinforced slope during construction

Fig. 15. Finished Project

3.4 Bangunan City Hall, Brunei

During the rainy season in December 2005, heavy rainfalls created soft soil conditions at the construction site of the Bangunan City Hall in Brunei. The fully saturated clayey subgrade did not provide sufficient bearing capacity to allow for the access of trucks delivering construction material to the site. In order to prevent a complete shutdown or delay of the construction work due to a shortage of construction materials, measures were necessary which could re-establish the trafficability on the site in a very short period of time.

In order to limit the costs for the necessary ground improvement work, it was intended to use an silty and clayey cohesive fill material available on site in combination with the geogrid reinforcement considered. The stiffness of the reinforcement layer plays an important role, especially where fine grained soils are used as reinforced fill on top of extremely weak soils.

The high flexural rigidity of the Combigrid® 30/30 Q1 151 GRK3 (Secugrid® 30/30 Q1 geogrid + Secutex® 151 GRK 3 separation and filtration geotextile) used provided a stable subbase even with the use of cohesive fill material. The possibility of using the fill material available on site reduced the overall construction costs and allowed for continuous construction works without any time lag on the site.

Fig. 16. Existing site conditions
base

Fig. 17. Limited rutting of the reinforced
courses

3.5 Rehabilitation of a Railway section near Weesenstein, Germany

The Elbe-River flood disaster in 2002 destroyed approximately 80 % of the infrastructure in the "Müglitztal" valley near Dresden. Close to the city of Weesenstein, an 11 m high railway embankment in the area of an undercut slope collapsed over a distance of approximately 100 m so that the rail traffic was cut off.

In order to get the rail traffic running again in the shortest possible time, the German National Railways (DB Projekt-Bau GmbH, NL Süd-Ost) and the planning company of EVP/GIV GmbH, NL Dresden, decided to install a reinforced soil structure with a steel grid formwork as a facing system as a temporary measure, as the Federal Railways Agency's standard guidelines do not approve the application of permanent geogrid-reinforced soil structures where they are subjected to rail traffic. In addition, the final structure can only be approved in accordance with a flood protection concept for the Müglitz River which, at that time, did not exist. The combination of a geosynthetic reinforcement together with the fill materials as a compound ensures the internal and external stability of the structure. The steel grid element stabilizes the slope face, and the geotextile non-woven separation and filter layer prevents the erosion of the fill material.

The approximately 5 m high geogrid reinforced part at the bottom of the slope is constructed with an approximately 60° inclination and is superposed by a 4 m high embankment.

The structural analysis for the reinforced slope was carried out on the basis of the German recommendations for geosynthetic reinforcements (EBGEO, 1997).

Fig. 18. Collapsed railway embankment after flooding

Fig. 19. Geogrid-reinforced railway embankment

The Secugrid® 120/40 R6 product applied has a Federal Railways Agency (Eisenbahn-bundesamt EBA) certification for this application. A 0/45 mm crushed mix acted as the covering material. The Secugrid® reinforcement element was installed in 10 layers at a distance of 0.50 m in line with the design analysis. The immediate interlocking effect of the Secugrid® with the covering material and the product structure demand the high transfer of forces and minimal deformation of the embankment both during the installation and under the traffic load. Structural deformations when installing Secugrid® do not need to be taken into account as any force occurring is immediately absorbed by the Secugrid®.

Within just a few weeks, the whole structure had been completed by a pool of 10 local construction companies using simple, fast and cost-efficient construction methods, so that the flow of regular traffic was quickly reinstated. Today, modern construction methods like these can prevent erosion hazards in times of flooding.

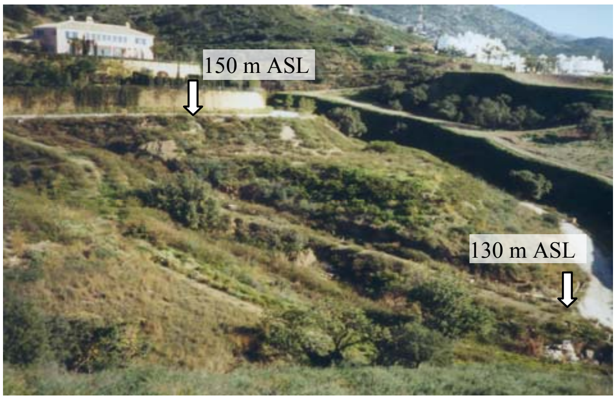
3.6 Reinforced Slope in Marbella, Spain

In the hilly landscape of the Andalusia coastal city of Marbella, which is located about 50 km west of Malaga, land for building is extremely expensive as well as difficult to develop as a result of the natural topography, which is characterized by a terrain inclination of about 45°.

The Spanish private owner planned to fill up the hilly site to create an area of 10,000 m^2 of land for building, for the construction of real estate. As an attractive landscaping with a natural sea view, the total area was separated by the owner into 3 main plateaux, which were stabilised by geogrid reinforced retaining walls and steep slopes.

In order to realize an attractive landscaping, various facing systems were chosen for the different wall and slope sections.

The final task was to construct three independently-located houses, including complexes of recreation facilities, access roads and gardens separated into individual sections with areas of 5,400 m^2, 3,000 m^2 and 3,000 m^2. The original situation of the particular area is shown in Fig. 20.



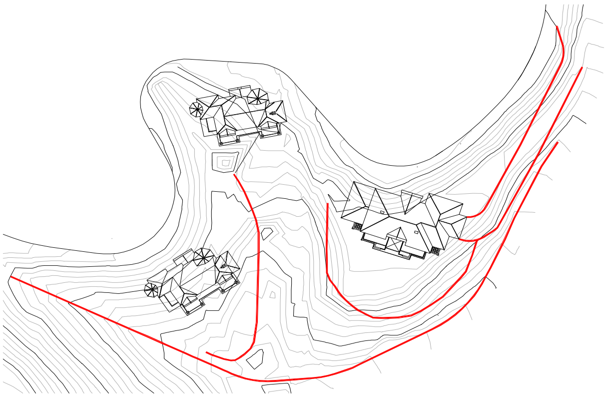


Fig. 20. Original site situations in the hills of Marbella / Spain

Fig. 21. Site plan view with 5 wall gradients separating the area

The aim was to provide reinforced earth structures to reach the maximum terrain level of 150 m ASL (the nominal level above sea level) starting from the lowest level of 130 m ASL by limiting the required maximum height with the characteristics of terraces.

A total of 5 main geogrid-land reinforced retaining walls and slopes were constructed to create the above-mentioned necessary building. Single geogrid-reinforced earth structures with lengths varying between 60 m and 200 m were required due to the existing topography and design requirements.

Inclinations of 90° (with small intermediate berms) and 70° (a continuous slope) were realised. For all the facing systems the wrap-around method was used. Pre-placed natural blocks as well as sacrificial galvanised steel grid meshes were chosen as facing. The steel grid meshes allow for a fast construction rate, because the steel meshes remain in place after the geogrid installation and fill soil compaction. The steel meshes provide a high degree of stiffness supporting a smooth facing.

The wrap-around-method includes the placing of vegetation soil (fine-graded top or humus soil) placed directly behind the steel grid elements. In order to avoid the wash-out of the fine-graded top soil at the wall face a Secutex® nonwoven separation and filtration geotextile was installed.

A primary geogrid is used for the wrap-around-method. The higher-strength geogrid was installed partly as a secondary reinforcement layer after placing and compacting the first 30 cm of fill soil. Due to the extremely dry summers in the south of Spain and the steep inclination of the bottom wall, an artificial irrigation system consisting of slotted pipes was installed in the facing system.

The geogrid-reinforced soil structures as a flexible alternative to concrete retaining walls allowed for the cost effective, attractive development of real estate in a difficult topography. A total of 5 different geogrid-reinforced soil structures were realised in Marbella to provide terraced plateaux filled with 40,000 m^3 of soil. The solution presented provides significant advantages concerning flexibility in geometry and cost-effectiveness in relation to the regionally expensive land prices and conventional construction methods.

Fig. 22. Construction of the base wall (10 m high)

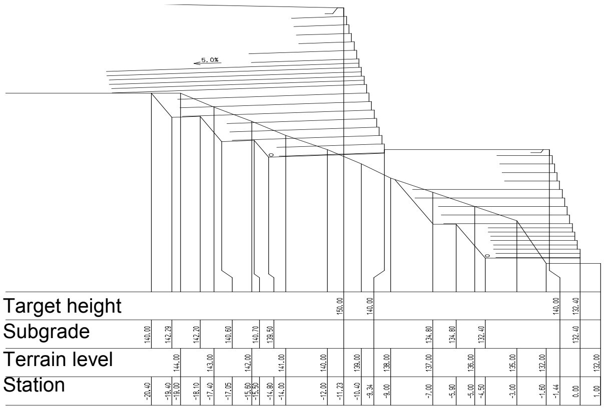


Fig. 23. Typical cross-section layout

Fig. 24. Installation of a natural stone block facing for the semi-circle geogrid reinforced soil structure (August 2003)

Fig. 25. Villa constructed on reinforced soil structure (May 2006)

4. Conclusions

The experience gained from the different case histories proves that with the use of high modulus geogrid reinforcement layers the load bearing capacity of soils can be significantly increased to extend service life by reducing deformations.

Even at extreme soft subgrade conditions, geogrids first of all allow for and secondarily improve the compaction of foundation layers.

This enables significant savings in foundation material in road or railway applications compared to unreinforced structures. The use of geosynthetic products will help reduce construction costs, especially when decreasing building material resources and consequential increasing prices.

Geogrid-reinforced soil structures allow for a quick and economic construction method for the rehabilitation of landslides and secondarily reduce construction costs as steep structures can be built which utilize reduced building land compared to natural slope inclinations.

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