STEEP SLOPE REINFORCEMENT WITH GEOGRIDS –
DEFORMATION BEHAVIOUR UNDER STATIC & CYCLIC LOADING

Jörg KLOMPMAKER, BBG Bauberatung Geokunststoffe GmbH & Co. KG, Espelkamp-Fiestel, Germany
Kent VON MAUBEUGE, NAUE GmbH & Co. KG, Espelkamp-Fiestel, Germany
Murray BANTING, Applied Geo-Environmental Solutions Inc., Calgary, Canada

ABSTRACT
The construction of geosynthetic reinforced slopes and retaining walls is continuously increasing and has already
developed to a state-of-the-art technology. Whereas the load-carrying capacity of geosynthetic reinforced soil
structures has sufficiently been examined and proven, details for the proof of the deformation behaviour of these
structures, especially under cyclic loading rarely exist. This paper will present results from laboratory and large–
scale model tests, which have investigated the interaction behaviour between soil and different types of
geosynthetic reinforcing elements in combination with the resulting deformation behaviour of the reinforced soil
structures under constant and cyclic loading. The paper ends with a case history about the construction of several
gеогrid reinforced soil structures, which were necessary to establish 10,000 m² of building land in the
mountainous area of Marbella (Andalusia) in Spain.

1. IMPACTS ON GEOSYNTHETIC
REINFORCED SOIL STRUCTURES

Vertical static impacts on reinforced soil structures
consist of the dead load of the soil and vertical
stresses resulting from permanent structures. The
static loading on the geosynthetic reinforcement can
approximately be determined by the resulting earth
pressure on the facing system and its distribution
over the connected reinforcing elements. Dynamic
impacts can result from:

- Dynamic impacts on the foundation resulting
  from traffic areas, construction operation as
  well as due to dynamic stresses of structures
- Dynamic impacts on structural parts due to
  crushes resulting from collision
- Earthquakes

2. DEFORMATION BEHAVIOUR OF
GEOSYNTHETIC REINFORCED SOIL
STRUCTURES

Several investigations concerning the load-carrying
capacity of geosynthetic reinforced soil structures
have come to the conclusion, that the installation of
horizontal reinforcing elements in soil can generate
an extremely complex composite material, which
offers a behaviour that is different from the
summation of the individual material parameters
(geosynthetic and soil).

From a mechanical point of view, the properties of
compound materials are mainly based on the
following aspects:

Geosynthetic: - Stress-strain behaviour (modulus)
  - Polymer / manufacturing technique
  - Aperture size
Soil: - shear strength parameters
  - Grain size
Compound: - Geosynthetic layer spacing
  - Type and magnitude of impact load
  - Stiffness of facing system
  - Allowable deformations

The load carrying capacity of geosynthetic soil
structures has been proven in large scale model
tests (Bathurst et al. 2003), with quasi monolithic
sliding wedges (Figure 1).
The sliding soil wedge is moving against the resisting soil. Due to sufficiently high tensile forces and a sufficiently high embedment length of the reinforcing element into the passive zone, the stability of the sliding wedge is assured. The proof of the serviceability is implied as being evidenced, when the load-carrying capacity can be warranted. Especially for geosynthetic soil structures which are susceptible to settlements (e.g. bridge abutments or retaining walls in railway applications), it is desirable for the warranty of the durability and the serviceability, to be able to forecast the deformations resulting from the effective loads and to compare those with the allowable deformations.

Several carried out and monitored projects confirm that the in-situ measured tensile forces of the geosynthetic reinforcing elements partly show lower values as they have been predicted by the design.

Due to the rheological properties of the geosynthetics only a small increase of plastic and thus non-reversible deformations develop at low load levels after the construction phase. With the low activated tensile forces under service load, the available tensile force reserves of the reinforcing element are not utilised in comparison to the calculated long-term design strength.

High geosynthetic tensile forces can only be activated after the loss of serviceability and lead to a high safety potential of the structure under service loads.

The safety potential of geosynthetic reinforced soil structures constitutes the necessity to adjust the load carrying capacity within the scope of the serviceability as well as the bearing capacity to the real conditions. This can only be achieved if the real load distribution inside the compound structure is determined. With the knowledge of the progress of stresses inside the reinforced soil structure, the effective forces can be estimated more precisely and the deformations under service load can be forecasted.

For the investigation of the deformations of geosynthetic reinforced soil structures under service load, the mechanical behaviour of the compound material, the influence of the individual material properties (soil and geosynthetic) and the interaction behaviour between both components has to be known.

1.1 Laboratory Model test – Deformation under static loads

The main aim of the model test (Bussert 2006) which is described in the following is the determination of the influencing factors for the interaction between geosynthetic and soil and the determination of the load distribution behaviour under static service loads.

For this, a particular section of a geosynthetic retaining wall is examined in laboratory tests. With the variation of possible soil and geosynthetic properties, the influence on the interaction and compound behaviour between soil and geosynthetic and the load carrying capacity of the resulting compound structure is determined.

With the distance-dependent registration of the activated stresses and strains inside the geosynthetic reinforced soil structure, the load carrying capacity reserves can be determined as a function of the deformations in the facing area.

For the determination of the boundary conditions of the laboratory test a continuous long geosynthetic reinforced soil structure was assumed. Based on the cinematic degree of freedom, only a horizontal deformation, transverse to the embankment axis can occur. Due to shear deformations inside the compound structure, horizontal deformations lead to vertical deformations at the top surface. The deformation is a two-dimensional state, where deformations only appear transverse but changes in the state of stress also appear parallel to the embankment axis. Deformations in the subgrade or the backfill are neglected.

For the investigation, a 9 m high retaining wall is assumed. From deformation measurements it is known that the biggest deformations and horizontal forces appear approx. at 1/3 or ½ of the wall height away from the toe of the structure (Bathurst et al. 2004, Rankilor 2004), which results in a decisive vertical load of 120 kPa on top of a 9m high wall. The test apparatus is shown in Figure 2.

![Figure 1 Determination of tensile forces in the geosynthetic reinforcing element](image1)

![Figure 2 Cross Section of Biaxial test apparatus](image2)
further contact of the movable steel plate to the four side elements besides at the plug gauges.

The stress which is acting on the steel plate during movement can thus be determined without any loss. The horizontal deformation of the movable plate is measured by three spacers that are mounted to the plate. On top of the spacers displacement transducers are attached in the centre of the plate as well as in the area of the bolts.

The vertical load on top of the test setup is applied by a hydraulic cylinder and measured by a pressure cell. The settlements of the load plate are monitored by inductive displacement transducers at the edges and in the centre of the plate. The stresses transverse to the direction of movement are measured by strain gauges which are applied to the plug gauges.

As fill material 3 different soil types were used:

- silica sand (0-2 mm)
- silica gravel (2-12 mm)
- gravel sand (0-36 mm)

To achieve constant test conditions, all soils were installed in dry condition. To guarantee a constant density of the installed soil layers, the sand or gravel was rippled through a punched plate. The density was controlled by the drop height and the hole diameter.

Several geosynthetics of different manufacturing types (woven, laid, stretched and knitted), different polymers (PET, PP, HDPE) and different stress-strain characteristics (modulus) were used in the tests.

The effectiveness of different geosynthetic reinforcing elements can explicitly be derived from the effective horizontal forces at the front face of the biaxial test apparatus. Due to the external loading and the steel plate movement at the front face, grain rearrangement and strains in the geosynthetic reinforcement lead to shear and tensile force activation in the compound material, which change the effective horizontal stresses.

In Figure 3 and 4 the maximum horizontal stresses of the compound material (geogrid & soil) are documented, which can be absorbed at an applied load of 120 kPa and a defined front movement of the steel plate.

Using sand as fill material a geogrid layer spacing of 0.4 m and for gravel a vertical layer spacing of 0.75 m has been used. In Figure 1 geogrid products with a tensile strength between 110 kN/m and 120 kN/m have been used whereas in Figure 4 results from geogrids with a tensile strength between 40 kN/m and 55 kN/m are documented.

Depending on the manufacturing technique (laid, stretched, woven & knitted) of the used geogrid a different effectiveness in relation to the maximum stress absorption can be determined.

In general it can be noticed that the laid geogrid shows the highest effectiveness in gravel as well as in sand. Due to a much higher flexibility of the woven geogrid in comparison to the stretched and laid geogrids, no effective fixed support of the soil is given, which allows a higher deformation capability of the compound material. A higher stiffness of the geogrid also leads to a higher stiffness of the compound material which encourages the stress absorption and low deformations.

Further tests within the investigation also document that woven and knitted products need an initial deformation before a reinforcing effect can be measured compared to an un-reinforced system.

Due to the production related pre-stressing of laid and stretched geogrids, immediate stress absorption without primary deformations of the compound material takes place. Dimensionally stable and high-modulus geogrids assure an immediate frictional connection with the surrounding fill and increase already the stress absorption capacity of the compound material prior to the movement of the facing.

The achievable maximum stress absorption of woven and knitted geogrids is much lower due to a missing stabilising effect in the beginning and the resultant soil movement within the compound material.
Whereas the overall bearing effect of compound materials reinforced with stretched and laid geogrids consists of a stabilising and reinforcing part, only a reinforcing bearing effect can be achieved with woven or knitted products.

The activation of the reinforcing effect is further a result of the stress-strain behaviour of the geosynthetic product. Due to the fact that a higher modulus of the used geogrid normally results in an increase of the dimensional stability, it is incidental that an influence on the bearing strength of the compound material is also given.

1.2 Laboratory Model test – Deformation under dynamic loads

There is still a need for clarification concerning the behaviour of reinforced soil structures under constant dynamic loads, as they are typical e.g. in the safety-relevant field of railway traffic loads.

To monitor the behaviour of geosynthetic reinforced soil structures under such dynamic loads, extensive large scale tests have been carried out at the University for Engineering and Economy Dresden (FH) in a 1:1 scale (Göbel, Großmann; 2006).

The reinforced soil structure consisted of 4 geogrid layers, which were installed with a vertical spacing of 0.4 m. The embedment length of the installed geogrids was 1.75 m and the width of the reinforced slope was 3m. The slope was built with an inclination of 70° (Figure 5). As fill material sandy gravel (0/32 mm) has been used.

As reinforcing element a laid and welded geogrid with a tensile strength of 60 kN/m (md & cmd) was used (Figure 6).

To be able to monitor the dynamic stability of the reinforced soil structure under realistic railway traffic loads, extensive devices for the measurement of the deformation as well as for the oscillating rates have been installed inside the structure.

As dynamic load an alternating load with a lower load level of \( \sigma_u = 14.5 \text{ kN/m}^2 \) and an upper load level of \( \sigma_o = 94.5 \text{ kN/m}^2 \) at a frequency of 7 Hz was applied to the structure with a hydraulic loading device. These loads typically represent a train with a speed of 200 km/h. In addition to those typical loads, also extreme dynamic loads (frequency of 28 Hz & 40 Hz), which rarely occur in practice, have been applied to the reinforced soil structure.

As a result of 12.8 million applied load cycles, maximum vertical deformations of 0.1 mm were measured (Figure 7), whereas the measured horizontal deformations were within the accuracy of measurement.

The applied vibration rates are very quickly absorbed over the depth as shown in Figure 8.
At applied vibration rates of 15mm/s, remaining values of < 5mm/s have been measured already at a depth of 0.50 m underneath the load plate. The magnitude of dynamic impacts on the geogrid directly depends on the depth. It is thus of great importance, at which depth underneath the dynamic load level the first geogrid level is installed.

With regard to this respect it is defined in Ril 836 that a minimum vertical distance from the top geogrid layer
- to the foundation level of 0.5 m
- to the formation level of 1.0 m &
- to the upper level of the rail track of 1.7 m

is required (Figure 9). These regulations have been made on the basis of the present standard of knowledge about the dying out of dynamic loads over depth and can be judged as very conservative. Due to this fact a very small distance between load impact level and top geogrid layer of 0.6 m was chosen in the large-scale test. Even under these extreme test conditions, the reinforced soil structure has proven sufficient load carrying capacity and serviceability.

After the test the top geogrid layer has been excavated. The results of the visual inspection can be summarized as follows:
- No damages of the geogrid could be recognized
- Between geogrid and fill soil a good interlocking has been detected
- Abrasion of the geogrid due to high dynamic loads could not be registered

To investigate the mechanical properties of the top geogrid layer after applying 12.8 Mio dynamic load cycles, samples have been tested to measure the remaining tensile strength of the geogrid. Based on the carried out tensile test according to DIN EN ISO 10319 a 3 % lower tensile strength of the installed geogrid was measured, in comparison to a sample from the same production lot that was tested during quality control.

Based on this results, a safety factor for installation damage and dynamic loads of $SF_{\text{Inst+Dyn}} = 1.03$ can be derived. According to Hubal (2000), a safety factor $SF_{\text{Dyn}}$ for the determination of the long-term design strength of the reinforcing element, considering dynamic effects resulting from railway traffic, have to be considered. Recommended values of $SF_{\text{Dyn}}$ are defined according to the depth of the geogrid layer underneath load level:
- $\leq 1.5$ m below load level : $SF_{\text{Dyn}} = 1.5$
- $\geq 4.0$ m below load level : $SF_{\text{Dyn}} = 1.0$

Interim values can be interpolated.

Based on the gained test results from the large scale laboratory test it can be concluded that the current standards underestimate the resistance of the tested geogrid against dynamic loads, resp. overestimate the propagation of vibrations over depth and thus have to be reconsidered to allow even more economic geosynthetic alternative solutions in comparison to conventional construction methods.

3. REINFORCED SLOPE IN MARBELLA, SPAIN

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

For the establishment of real estate, the Spanish private owner planned to fill up the hilly site to create an area of 10,000 m$^2$ of building land. As an attractive landscaping with natural sea view, the owner separated the total area into 3 main plateaux, which were stabilised by geogrid reinforced retaining walls and steep slopes. To meet an attractive landscaping, different facing systems have been 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 an area of 5,400 m$^2$, 3,000 m$^2$ and 3,000 m$^2$. The original situation of the particular area is shown in Figure 10.

The aim was to provide reinforced earth structures to reach the maximum terrain level of 150 m ASL (nominal level above sea level) starting from the lowest level of 130 m ASL by limiting the required maximum height with characteristics of terraces.
In total 5 main geogrid reinforced retaining walls and slopes have been constructed to create the above mentioned necessary building land. Single geogrid reinforced earth structures with lengths varying between 60 m and 200 m were required due to the existing topography and design requirements (Figure 11).

Two different types of a laid and welded geogrid, manufactured by Naue GmbH & Co. KG, have been installed for these civil works:

- **Secugrid® 80/20 R6** (primary reinforcement, which is installed with wrap-around-method)
- **Secugrid® 200/40 R6** (installed at half of normal layer spacing as secondary reinforcement)

**Secugrid®** is a laid geogrid made of stretched, monolithic polyester (PET) flat bars with welded junctions. The subsoil characteristics are based on in-situ probes.

The mountainous region of Marbella is characterised by rocky slopes with bedrock. It is assumed that the subsoil consists of undisturbed rock with sufficient bearing capacity for the planned structures. The subsoil stratification of the mountainous terrain can be characterised as follows:

- In depths of 0.0 m to 2.0 m below terrain level: in-situ filled soil with roots, bushes and turf (removed for construction)
- In depths of 0.6 m to 4.5 m below terrain level: weathered Phyllite has been encountered by probe tests.

For the reinforced fill the design requirements have specified granular soil with large compaction capability and water permeability coefficients of \( k_v \geq 1\times10^{-5} \text{ m/s} \) to prevent the build up of hydraulic pressures inside the reinforced soil structure. The maximum grain size diameter should not exceed 63 mm (\( d_{\text{max}} = 63 \text{ mm} \)), which has been taken into account for the calculation of the long-term design strength for the geogrid, considering the product specific installation damage reduction factor.

Inclinations of 90° (with small intermediate berms) and 70° (continuous slope) have been realised. For all facing systems the wrap-around method has been used. Pre-placed natural blocks as well as sacrificial galvanised steel grid meshes were chosen as facing. The steel grid meshes allow 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 stiffness supporting a smooth facing.

The design has considered a vertical geogrid layer spacing of 60 cm. In the vicinity of the facing elements small manual vibrating compactors have been used. The wrap-around-method includes the placing of vegetation soil (fine-graded top or humus soil) placed directly behind the steel grid elements. To avoid the wash-out of the fine-graded vegetation soil at the wall front a Secutex® nonwoven separation and filtration geotextile has been installed.

The 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.

The required embedment lengths resulting from the stability analysis were documented in implementation plans and drawings achieving easy installation plans. For each wall individual geogrid layout plans and cross-sections have been prepared to allow an accurate installation. Figure 12 and 13 show the first and largest (10 m high) geogrid reinforced earth structure during construction.

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, has been installed to the facing system.
In total 5 different geogrid reinforced soil structures have been realised in Marbella to provide terraced plateaux, filled up with 40,000 m$^3$ of soil. The presented solution provides significant advantages concerning the flexibility in geometry and cost-effectiveness in relation to the regionally expensive land prices and conventional construction methods.

4. CONCLUSION

Based on the presented test results from the investigated reinforcing elements in large scale model tests it can be concluded that current design standards for reinforced soil structures clearly underestimate the effectiveness of geosynthetic reinforcing elements with regard to:

- Resistance to dynamic loads
- Interaction behaviour between soil & geosynthetic
- Load transfer mechanism inside the compound material (soil & geogrid)

The results of the presented investigations also show that product properties of different reinforcing materials, like e.g. modulus and dimension stability (stiffness) have a decisive influence on the stress absorption of the compound material and its deformation behaviour. Current design standards do not completely allow for the consideration of these influencing factors.

Geosynthetic reinforced soil structures often offer ecological and economical advantages compared to conventional construction methods like e.g. gravity or angular retaining walls as shown in the documented case history of geogrid reinforced soil structures in Marbella, Spain.

Soong and Koerner (1999) have shown that the costs for geosynthetic reinforced retaining walls are only half, compared to those of gravity walls.

The consideration of the new cognitions in combination with further investigations will help to design safe and even more economical steep reinforced soil structures.
5. REFERENCES


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