EXPERIENCES FROM DEFORMATION MEASUREMENTS ON GEOSYNTHETIC REINFORCED RETAINING WALLS

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Abstract: Numerous geosynthetic reinforced soil structures have been constructed successfully to satisfy demanding conditions such as soft subsoils, very high traffic loads and very high structures. Where these structures have been instrumented the results have shown that the measured geosynthetic strains are significantly smaller than those predicted by the design process and hence the structures may have a much higher margin of safety than is necessary. The geosynthetic strain levels have been shown to be so low that the effect of creep is also negligible.

The analysis of this monitoring information has not yet been used to optimise the design methods or to change the design approach to one based upon deformation.

The results of a number of these monitored structures are presented and compared with the findings of a laboratory based project investigating the factors controlling the stress-strain behaviour of reinforced soil in structures. A better understanding of the mechanisms could then lead to more efficient and realistic design.

Keywords: geogrid, composite, serviceability, deformation, strain.

INTRODUCTION

The use of geogrids to ensure temporary and long-term stability of slopes and walls is an economical and ecological alternative to traditional structural solutions as gravity walls or cantilever beams e.g.. Especially due to the economic advantages compared to classical solutions an increasing use of geogrid reinforced structures has been constructed in the last decades. The well known advantages of high load carrying capacity and small facing deformation as well as insensitivity to differential settlement have been proven under difficult and variable conditions. As confidence in geogrid reinforced structures increased the application was expanded. Construction of slopes with more than 20m height or loading with high concentrated loads as in bridge abutments can nowadays be regarded as state of the art.

Figure 1. A9 during construction stage and after full vegetation

The stability is calculated based on simple methods that do not fully take the interaction of geogrid and soil in account to be able to show the full benefits of the structures. Therefore the developed design methods for geogrid reinforced soil walls have been generally accepted to be very conservative in determining the density of reinforcement required for stable structures. Instrumented structures showed that even under additional surcharges or dynamic loadings only extremely small structural deformations occur. Additionally, the expected increase in strain under continuous tension loading in the soil is hardly measured and tends to be conservative.

In structural and mechanical engineering it is the normal case to describe the load transfer in the structure based on mechanical models. It is therefore possible to calculate the expected structural deformations based on these models. Dependent on the accuracy of the model more or less reasonable agreement between load and deformation can be calculated from unloaded conditions to failure loads. Due to the complexity of geogrid-soil interaction and the rheologic behaviour of the geogrids themselves an extremely large and uneconomical deviation between calculated and observed failure capacity and related deformations is calculated. This shows that the adopted mechanical model for geogrid reinforced soil is not representative for all kinds of geosynthetics. A fairly better could be achieved if the gained knowledge so far would be taken into account to estimate structural deformations.

ACTUAL DESIGN PROCEDURE

In most European calculation methods the proof of stability is based on the principles set out by the British Standard BS8006 (1995). According to BS8006 equilibrium of a monolithic active zone to the resisting zone is warranted by introducing sufficient geogrid tensile strength to carry the weight of the active zone. The interaction of geogrid and soil is tested by pullout or shear tests. Different failure modes that have to be checked which are regulated in the national design procedures. Tests on finished structures calculated according to this design method indicate that the load carrying capacity can exceed the calculated failure loads by numerous times. This has been proven impressively in various structures (Bräu, Bauer, 2001). Additionally it has been noted that the measured deformations during these tests are much smaller than the predicted ones.

To calculate deformations of geosynthetic reinforced soil structure different approaches are possible. Dependent on the required accuracy they can be simple or advanced, but they have in common that the results do not reflect actual behaviour.

Any facing deformation is the result of underground deformation, deformation of retained fill as well as deformation of the reinforced earth. Calculation of the reinforced soil deformation is usually approximated by deriving the expected strain from the theoretical tension force between active and passive zone. The geogrid elongation under this force is derived from the isochrones and the anticipated design life. It has been shown numerous times in the past that the estimated strains from this method are leading to deformations that were never measured.

Due to the numerous knowledge gained by the observational method or by trial walls (strain and earth pressure measurements or survey of facing deformation) is it known that the measured strains in the geosynthetics in the geogrid-soil composite are much smaller than calculated. At the same time the measured earth pressure is, dependent on the position of the earth pressure cell, significantly smaller than calculated. Comparable to this the facing deformations even under long-term observations are extremely small. This was also observed in cases were the applied loadings exceeded the design loads. The measured geogrid strains as well as the earth pressures are much smaller than expected leading therefore to smaller elongations due to continuous loading.

As it has been shown numerous times that the deformation calculation based on the isochrones is exceeding the measured deformations it seems to be more reasonable to estimate deformations based on gained experience or alternative calculation approaches. According to the German DIN 1054 serviceability calculation can be based on experience if sufficient data is available. With sufficient data on comparable structures a more accurate and therefore more economic usage of the geogrid-soil can be achieved, ensuring a sufficient security level.

FINISHED STRUCTURES

Following some finished structures will be described showing the numerous application areas for geogrid reinforced structures as well as the knowledge obtained. They have been monitored extensively so that the stress-strain of the composite can be deduced.

Motorway BAB A9, Hienberg-Aufstieg, Germany

Due to the widening of the A9 (Berlin-Nuremberg) a 15m high reinforced slope with an additional 8m high top berm and a face inclination of 60deg was build in June 1998. A detailed report of the 250m long structure was given by Stiegeler, Floss (1999). Due to the optimal adaptation of the structure that was reinforced with Tensar SR110 geogrids to the difficult geometrical conditions as well as varying subsoil parameters a very economically solution was constructed in a short period, see figure 1 and 2.

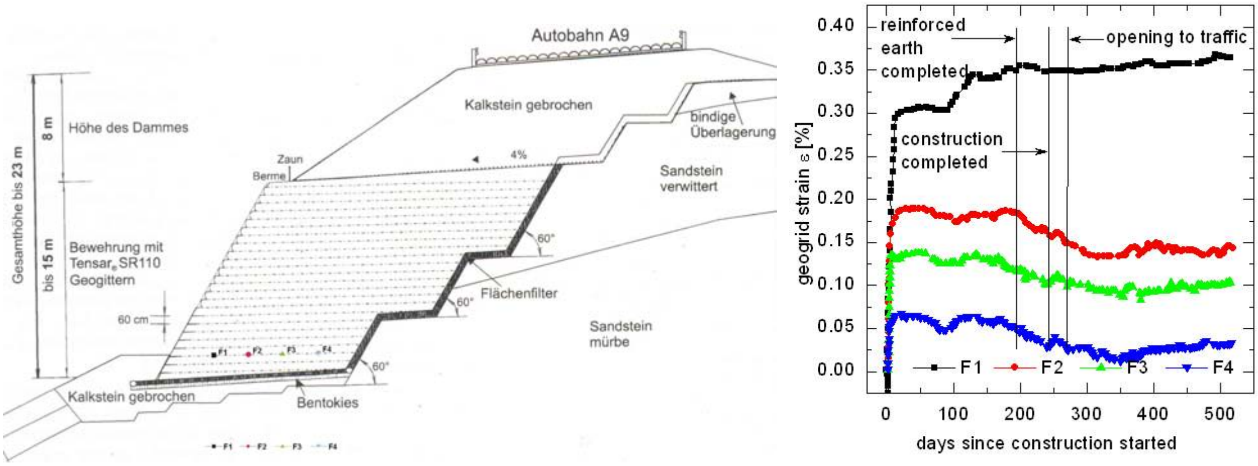

Figure 2. Cross section of the structure, measured strains during first 1.5 years of service

Measurements of earth pressure, geogrid strains and facing deformation were started already during construction. The information gained showed the influence of the construction process on the deformation behaviour. The measured geogrid strains show a strong increase during the initial construction state and stay nearly constant as construction proceeded. Only one measurement (F1), see figure 2, indicate the resumption of construction work after 100 and 170 days by a slight increase in measured strain. In the first 9 month after opening to the traffic (at 250 days) no increase in strain under constant loading was observed, that could indicate geogrid creep (Stiegeler, Floss, 1999). Instead of an increase all measurement locations except location F1 show a slight decrease of measured strain.

As indicated by the measurements around 95% of the strain is activated during the initial construction period. Further construction leads only to a small increase in strain and shows only a slight increase or remains constant. After or even during construction of the structure even strain reduction can take place. The strain development in the initial part of the construction depends on the compaction energy that was applied and that is stored in the ground. It is clearly visible that the measurements show scatter and the activated strains within the structure are not equal. The scatter depends on the measurement position in the reinforced structure, soil inhomogenities as well as the geogrid properties. Strains near the facing tend to be larger and decrease with increasing distance from the facing.

While strains after construction slightly increase near the facing (F1) strains behind the facing reduce and stay nearly constant even 1.5 years after construction. No significant increase in measured data was observed since the structure was opened to the traffic. Calculation of the required strains to ensure equilibrium according to different design methods varies between 1.0 and 2.1% in short term testing lab testing. As the measured strains are larger and represent in-soil behaviour they indicate that only much smaller values are required to achieve equilibrium.

Temporary railway track in Karlsruhe (Germany)

In 1989 the access to Karlsruhe main station was modernized. Two bridges were deconstructed and replaced by a new one. As construction had to be finished during trafficking a temporary structure was build. A 5m high geogrid reinforced soil wall with a face inclination of 84deg was build. Deformations of the structure were measured showing typical deformation behaviour. The maximum measured deformation of the Tensar geogrid reinforced structure is 5.4mm, see figure 3. The structure was subjected to traffic loads during 1.5 years with heavy goods and passenger trains with a speed up to 120km/h, see figure 3. Afterwards 1.5 years the dam directly next to the existing structure was finished.

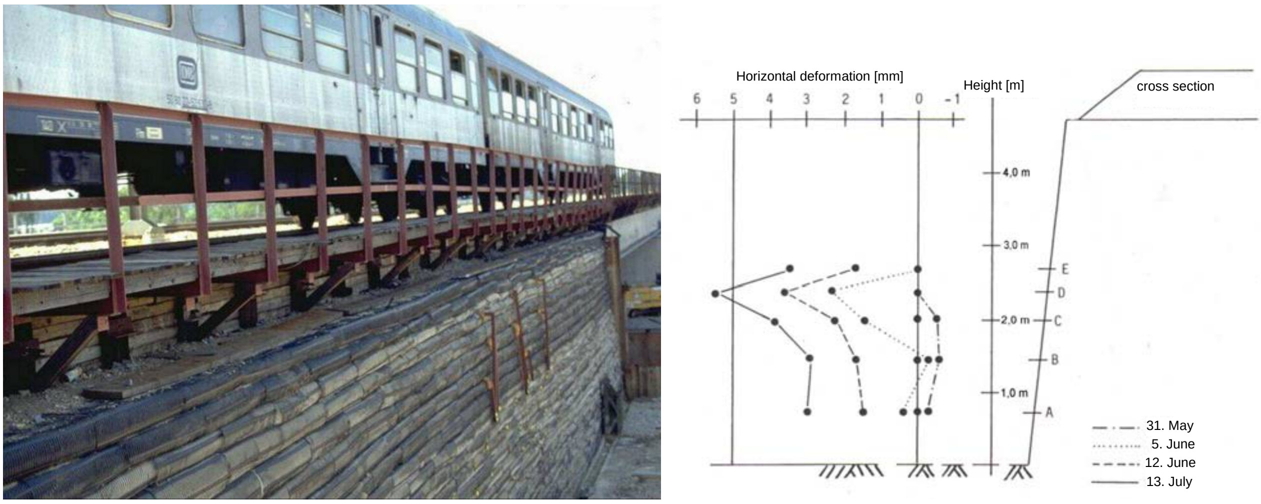

Figure 3. Structure during traffic loading, measurements of the face deformation

10 years after the structure was build a test sample of the highly loaded uppermost geogrid layer was excavated and tested in the lab according to DIN EN ISO 10319 (1999). No strength reduction was observed when compared with the initial strength of the geogrid, which demonstrated long term stability of the Tensar SR110 geogrids (Jenner, Nimmesgern, 2001).

Heavy good vehicle road Aalen (Germany)

The heavy good vehicle traffic road Aalen – Heilbronn is specially constructed for the transportation of heavy and extremely goods. In the town of Aalen, the run of the road was shifted from the centre to the outskirts. Due to the required relocation and the desired increase in allowed traffic surcharge an existing bridge over railway tracks had to be renewed. To be able to have a sufficient bearing capacity the subsoil, mainly consisting of sensitive alluvial clay und weathered clay stone with varying thicknesses had to be improved by vibrated stone columns, see figure 4. A 240m long and up to 14.9 m high access dam was constructed over it to connect the existing road to the bridge. Due to the limited available space the access road had to be constructed as a reinforced structure. To optically reduce the height of the reinforced structure the facing was divided into two sections. The lower part up to 5.5m height was protected to vandalism by a gabion structure. For an interesting and varying view of the facing the front was constructed with stones in different colour with a size of 100/300mm. On top of the gabion wall a 2m wide berm followed by a green slope with an inclination of 63deg up to a total height of 14.9 m was constructed.

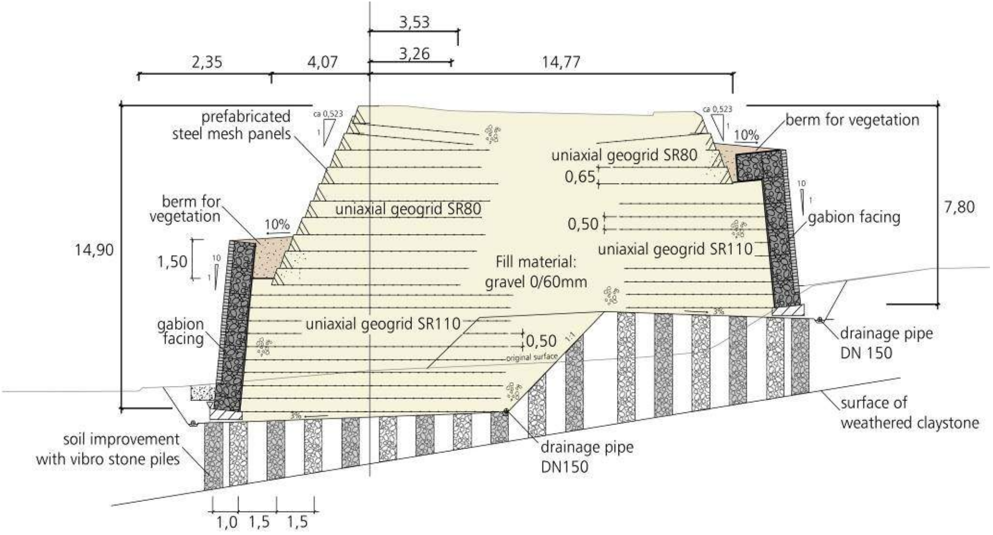

Figure 4. Cross-section of the access dam

Measurement readings were taken immediately after start of the construction to monitor the development of stresses and deformations. Geogrids as well as the reinforced soil were instrumented with different measurement devices to measure the stress-strain relationship inside the reinforced structure. Measurements of the facing deformation indicate a maximum outward movement of 10 mm. The measured strain of the Tensar SR80 and Tensar SR110 geogrids are max. 0.4%.

Settlement below the structure was measured by horizontal inclinometers. The time-settlement relationship indicated in figure 5 shows that the final settlement is already reached. The settlements measured are in an order of 2 – 4 cm. All values measured are far below the expected values due to the difficult subsoil conditions serviceability of the structure can be ensured for long term. The structure was finished in 2004 (Hägele, Hübel, 2005).

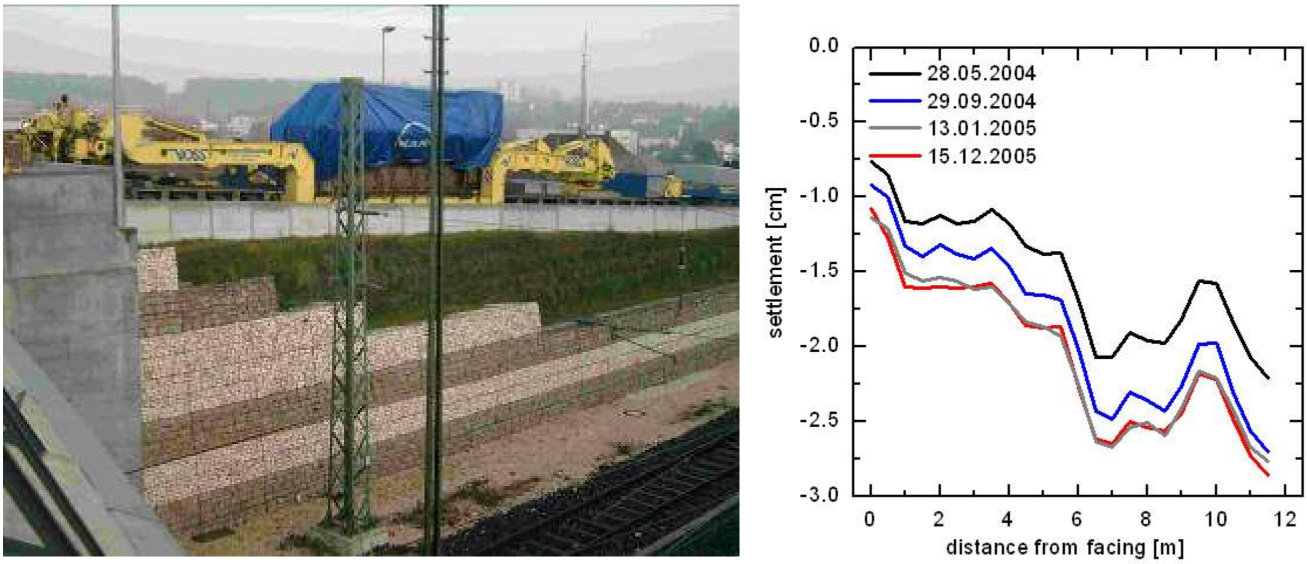

Figure 5. Condition during test-loading, measured settlement under the structure

The construction is scheduled to be trafficked weekly with extremely heavy special-purpose vehicle with a length of up to 70m and a load of 375 ton. As the impact of these loadings on the behaviour of reinforced structures is not known yet, an extra tour was made to be able to assess the impact of the loading on the overall behaviour, see figure 5. During the test loading with the stress development inside the structure and the deformation of the face as well as the strain behaviour of the geogrids was measured. Even under a constant loading for 20 hours only a very small deformation increase was measured.

The accuracy of the deformation measurement on the facing was determined by measuring the deformation of an unloaded section simultaneously. This indicated that the accuracy was in an order of ± 2 mm in horizontal and ± 3 mm in vertical direction. All values in the loaded section were below this accuracy and reduced to zero after the load was removed. Therefore the loading imposed only elastic deformations in the structure. Since completion of the structure the geogrid strains remain constant, indicating maximum strain in an order of 0.4%. The mean strain values are even substantially lower. Due to the trafficking test maximum strain differences compared to the initial values of 0.16% were measured, which decrease to 0.06% after the load was removed.

The test loading resulted in only small horizontal and vertical earth pressure changes that were below the expected values. The vertical earth pressure changes were, dependent on the position of the earth pressure cell, in an order of 3 to 10kPa. The horizontal earth pressure changes were independent of the cell position and in an order of 1 to 2kPa. The stress changes were completely elastic and reverted to the initial value after the load was removed. The serviceability of the structure was proven by this load test and opened to regular traffic.

Founders/ Meadows Bridge abutment

When geogrid reinforced structures are build to support settlement sensitive structures, more restrictive requirements have to be fulfilled to ensure structural serviceability. Accurate information on the expected deformation and the expected deformation behaviour during the service life of the structures is required to be able to determine serviceability.

Especially when the geogrid reinforced structure is supporting the bank seat of a settlement sensitive bridge abutment special requirements need to be fulfilled. To ensure serviceability limit state the maximum allowable strain increase during design life is limited to 0.5%. By ensuring stability and serviceability the use of geogrid reinforced structures can be considered for this type of application.

Abu-Hejle et al. (2002) published the results of an 8.9m high bridge abutment that was build at the intersection of Highway 25 and 86 in Colorado, see figure 6.

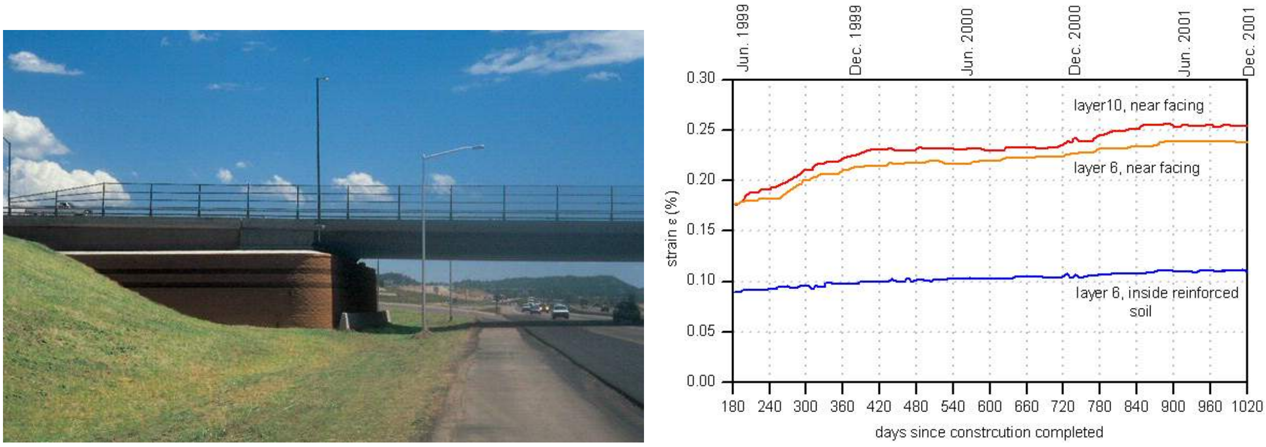

Figure 6. Meadows bridge abutment after opening to traffic, measured strain development in the first three years

Dependent on the theoretical utilisation of the geogrids designed according to AASHTO (1997), geogrid with different strength were used. This resulted in an optimized geogrid utilisation ratio according to the theoretical assumptions in the design method. During construction the measured geogrid strains increased nearly linear with height. After completion the measured strains are in an order of 0.2% and therefore significantly lower than the theoretical design values. The strain increase due to loading by the superstructure was significantly lower than the estimated values. Finally the strain increase during traffic loading was smaller than calculated. The measured additional strain decreased in the first three years from 0.09% to 0.04% and 0.02% in the third year. From figure 9 it can be seen that the strain values are reaching a residual value. Even under a conservative assumption of a linear strain increase throughout the whole design life, the strain at the end of design life doesn’t exceeding the allowable values.

COMPARISON AND CONCLUSIONS DRAWN FROM THE MEASURED VALUES

From all projects described it is obvious that the measured geogrid strains are much lower than the estimated values during design of the structures. Long term observations show that the measured values are nearly constant throughout the observed time, which covered up to ten years ore more. Therefore the measured behaviour can be regarded as representative for design life.

It is obvious that the activated geogrid strain is nearly equal in all structures, ranging from 0.05 to 0.04% as summarised in figure 7. The activated geogrid strain seems to be independent of the structural height and the position in the structure where the strain is measured. Therefore the measured geogrid strain is independent of the type of structure, the design method or the geogrid strength used. Even under unfavourable conditions (e.g. very high and long lasting loads, varying underground strength and stiffness or deformation sensitive structures) only extremely small variations and nearly not recognizable changes in soil stresses were measured. It is apparent that measured geogrid strains behind the facing seem to increase slightly while horizontal soil stresses and measured strains in the so called passive part of the structure tend do decrease or stay constant.

The residual values for each structure are reached after 2 to 3 years, depending on the loading conditions of the structure and the degree of compaction during construction. Measurements of facing deformation where during the observed times within the accuracy of the measurements used. This indicates that the changes in measured strain represent rather local rearrangement of stresses and strains than an increase in structural deformation. Increase in structural deformation would indicate ongoing movement of a specific area of the reinforced structure and cause a failure plane to develop, resulting in deformations larger than the allowed ones. Rearrangement of stresses and strains takes place as a result of non-uniform compaction during building of the structure as well as non-uniform stresses developed in the geogrid-soil layer when particles are squeezed in the geogrid apertures, causing soil confinement in a specific area around the geogrid. This rearrangement can take place in the first years after completion of the structure, depending on the applied loads.

The strain level measured in all instrumented structures represents the elastic range of geosynthetics. When only elastic components are activated, no creep can occur within the geosynthetic. When only elastic components are activated, measured strains remain constant during constant loading. They return to the initial values when the load is removed. It has been shown by Nimmesgern, Lieberenz (2001) that the stress-strain curve measured from a geogrid that was recovered from a structure after more than 10 years of continuous loading did not show a reduction of tensile resistance. The measured strength was compared with the quality control strength and indicated only small differences that were within the 95% confidence limit in accordance with ISO 2602:1980 (BS 2846: Part 2:1981).

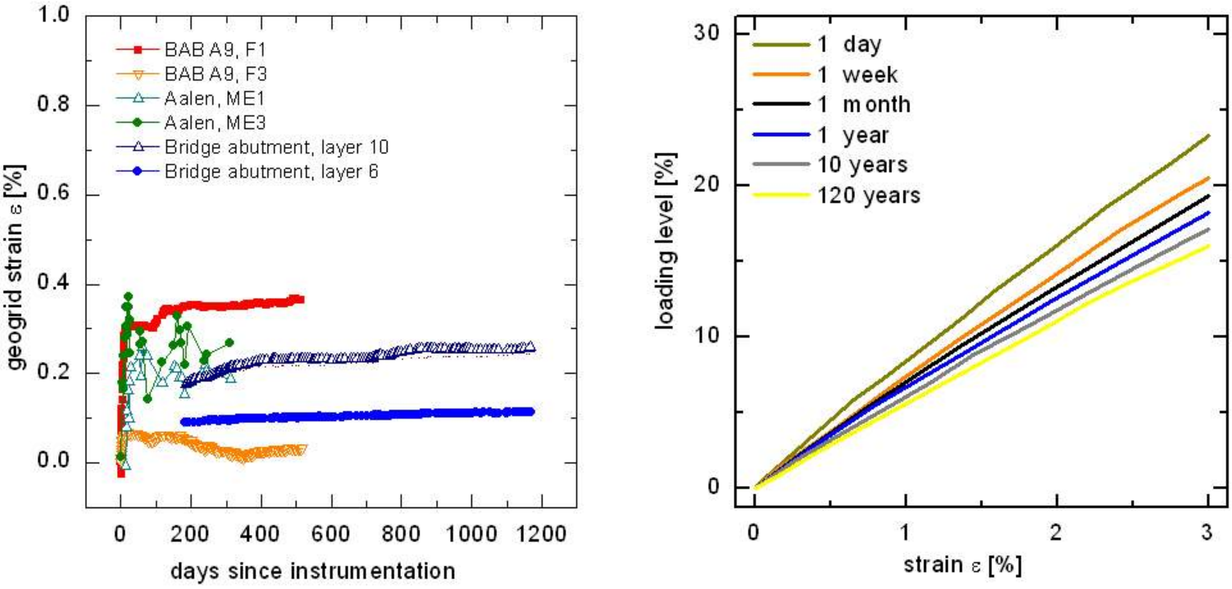

Figure 7. Comparison of measured strains in all structures, initial stress-strain curve for a HDPE-geogrid

According to the current design methods, the increase in strain of synthetics under increased tension force can be estimated from the isochrones. The Isochrones describe the rheological behaviour of the thermoplastic geosynthetics up to failure. For practical reasons a strain level of maximum 10% (in air lab test) and contain information about the expected strain increase dependent on the degree of utilisation and the duration of the test. The expected strain increase can be estimated based on loading level and design life. The smaller the loading level is, the smaller the expected strain increase is. To be able to give more precise information on the expected strain increase, only the initial part of the stress-strain curve up to 3 % needs to be investigated, see figure 7.

When estimating the strain increase for the measured strain level (<0.4%) only very small strain increase can be estimated after the structure is finished (assumed 1 month) up to design life (120years). This correlates very well with the measured strains in the field, but at the same time they indicate that the design methods and the determination of geogrid strain increase based on the rheological properties of the geogrids need to be evaluated. The loads measured in the field are smaller than the loads calculated during design for serviceability limit state. When the design loads are taken as a basis to determine the increase in strain by the isochrones the designed higher initial strains lead to larger strain increase than in the case of small initial strain. This indicates that the designed tension forces in the geogrid are not representing field behaviour as well as preferred for a reasonable design that enables the designer to estimate deformations based on actual behaviour.

COMPOSITE MATERIAL BEHAVIOUR

As the strain level in all described structures is nearly equal and independent from the strength of the geogrid used, the tension force activated in the geogrid differs due to different geogrid stiffness. Therefore the activated tension has a minor influence on the stress equilibrium between driving and resisting forces in the structure. Instead of the activated tension force, the behaviour within a geogrid reinforced soil structure is governed by the interaction of geogrid and soil. Due to soil confinement which is activated during compaction the theoretical stress-strain behaviour of the unreinforced soil is considerably improved. The soil confinement and therefore the improved stress-strain behaviour of the soil govern the stress-strain behaviour of the geogrid-soil composite that is activated when the soil in the geogrid apertures is confined.

So far nearly no reliable data on the stress-strain characteristics of reinforced soil is available. Therefore it is not possible to take the stabilising effect of the geogrid on the soil into account during design. This stabilising effect controls the mechanical behaviour of the geogrid-soil composite. To obtain more reliable information on the expected deformations in the field it is therefore suggested to base statements on the expected deformations from previous projects. Due to extensive measurements taken in the last decades a large database was developed containing information on numerous projects under various kinds of subsoil or loading conditions.

The properties of the composite material can be summarized as follows:

- Deformations are smaller than predicted
- Geogrid strains in serviceability state are smaller as theoretically calculated; strain increase as calculated by the isochrones is leading to too large values.
- Measured strains indicate that strains are in an order of 0.4% which is too small to activate the rheological behaviour of the geogrids
- Possible strains to reach soil failure and therefore lost in serviceability are in an order of 2-3%.
- Deformations cannot be predicted for all structures, deformations need to be assessed based on the properties of the geogrid-soil composite
- The stress-strain properties of the composite are nearly independent of the geogrid properties
- Long term properties are currently better assessed on experience based on observational method than according to the actual design
- The factor of safety against failure of the structure is much higher than calculated according to actual design.

To further investigate the influence of the soil stabilisation a reinforced structure for research purposes was build in an open pit mine. To investigate the influence of numerous elements of the structure, different geogrids, soil grain size distribution and facing types were constructed. The deformation of the facing as well as the geogrid strains were measured during construction and during the first years of service life. All parts were built based on information gained in the last decades instead of fulfilling actual design requirements. By varying layer spacing, geogrid stiffness and the grain size distribution it was shown that the actual deformation depends on the composite material behaviour rather than the geogrid strength. Even with higher strength and stiffness larger deformations can be obtained than by using lower strength with an optimised grain size distribution as fill material.

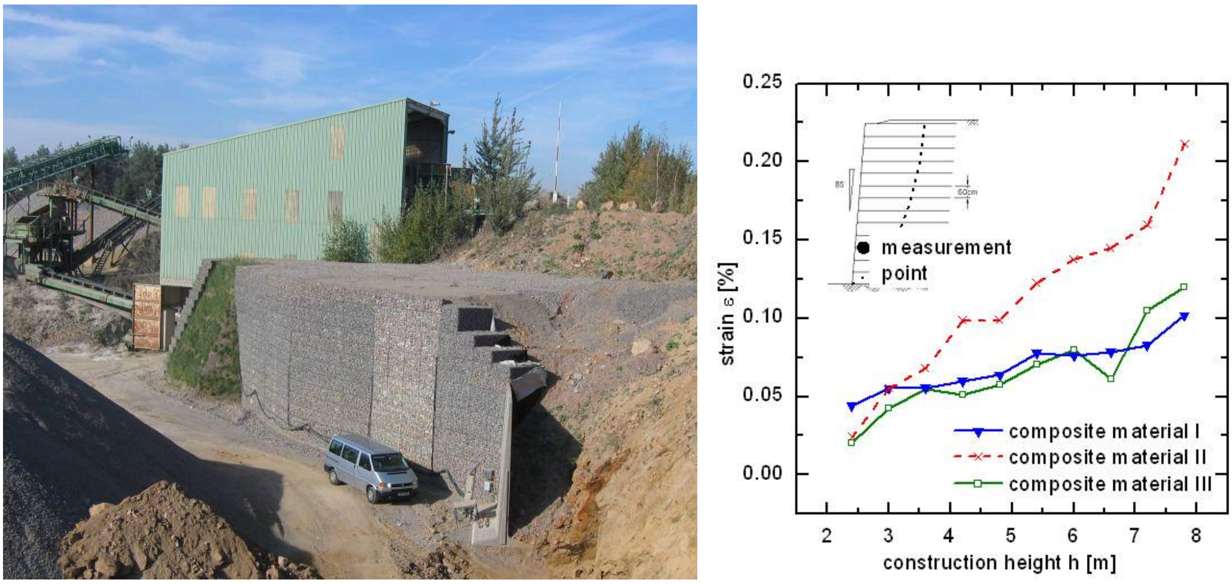

Figure 8. Structure build and strains measured during construction

From figure 8 it can be seen that all composite materials develop a nearly linear geogrid strain increase during construction. The measured strains at the end of construction are comparable to the ones measured in all the structures described before and much lower than the values obtained by the actual design procedures. This is observed for all cases even though a much lower geogrid strength than in the described structures were used. Once construction is finished, the measured strains stay constant with extremely small variations taking place. Facing deformation measured after placement of every soil layer indicated that a residual deformation value was already achieved during construction, depending on the composite material properties.

SUMMARY

A lot of instrumented structures build in the last decades were monitored over numerous years. All structures showed very small geogrid strains during construction and nearly constant strains after the structure was finished and opened to regular traffic. Even after years of loading the measured facing deformations and geogrid strains remain constant at considerably lower levels than the expected strains calculated during design. As deducted from these observations as well as shown by different research structures build in the past it is obvious that the load carrying capacity of the structures is considerably higher than the designed value. This behaviour was observed under different subsoil conditions, high traffic loadings and a theoretical high loading of the geogrids it is believed to be representative for numerous structures build with geogrids that were made from extruded, punched and oriented HDPE sheets.

The improved behaviour of the geogrid reinforced structures is developed during compaction of the soil over the geogrid. Soil particles are squeezed in the aperture and are therefore confined which results in an optimised stress-strain relationship with higher frictional resistance than the soil alone. This shows that it is necessary to over think current design needs and to develop an improved understanding of the actual stress transfer in the composite material to be able to obtain a more realistic design approach. Several geogrid and soil properties that are not taken into account in actual design (aperture size, aperture stability, geogrid stiffness) do have a high influence on the deformation behaviour of the reinforced structure. An assessment of deformation behaviour is therefore only possible when a sufficient database was build up in the past based on numerous instrumented structures. Simple estimations based on the stiffness of geogrids are not sufficient as the deformations depend to a large extend on the properties of the geogrid-soil composite.

The findings and conclusions drawn were proven in a research structure that was designed based on the experience gained. Numerous factors that are not taken into account in the actual design procedures were varied, showing their influence on the overall deformation behaviour.

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