The Use of Geosynthetic Reinforced Structures Working as Bridge Abutments in Scandinavia and Europe

M.-T. van Keßel
HUESKER Synthetic GmbH, Germany, vankessel@huesker.de

B. Thesseling
HUESKER Synthetic GmbH, Germany, thesseling@huesker.de

ABSTRACT
The main focus of this paper is directed to the geosynthetic reinforced slopes or walls which have already been built with heights up to 41 m. Typically multiple horizontal layers of geosynthetics, mainly geogrids, are filled with compacted granular material and arranged on top of each other with a vertical spacing of 0.4 m – 0.6 m. In order to prevent slope failure the required design strength and length of the single geogrid layers has to be estimated in a geotechnical design. The paper includes a short overview of European guidelines that regulate the design and the construction of structures using geosynthetics e.g. "Nordic Guidelines for Reinforced Soils and Fills" (2005).
With international case studies and a large scale test the development of geosynthetic reinforced structures specifically for bridge abutment applications is demonstrated. In 1991 for example the construction of geosynthetic reinforced walls working as bridge abutments over the Nyborg-Fredericia main railway line in Ullerslev was instructed by the Danish State Railways (DSB). After an almost 25-year service life the design, the construction and the settlement behaviour are described in this paper.

Keywords: Bridge Abutments, Geosynthetics, Retaining Structures

1 INTRODUCTION

Geosynthetics have been used effectively to overcome many geotechnical, roadway, hydraulic and environmental issues during the last decades. The geotechnical applications mainly include geosynthetics performing the reinforcing, separating and stabilizing functions. Thus they enable the improvement of structures on soft and even organic soils as basal reinforcement elements, they provide reinforcement above concrete piles or as Geosynthetic Encased Columns (GEC, Alexiew et al., 2012). This paper focusses on the introduction and description of geosynthetic reinforced retaining structures (GRS). In general these types of structures are frequently used to construct steep slopes or vertical to sub-vertical retaining walls. Due to the high load carrying capacity, (see Alexiew and Detert, 2008 and section 3.2), of geosynthetic reinforced retaining structures they have also been utilised for bridge abutments all over the world and in the process have become an established construction method.

2 GEOSYNTHTETICS

2.1 Characteristics and Functions

The term 'geosynthetic' includes a wide range of products produced from synthetic raw materials like Polyester (PES), Polypropylene (PP), Polyvinylalcohol (PVA), Polyamid (PA) and Aramid (AR). They are generally used in geotechnical constructions for separating, filtering, draining, reinforcing, protecting and sealing purposes. Best known representatives are perhaps non-woven and woven geotextiles, uni- or bi-axial geogrids and geocomposites. Geogrids can be produced by knitting or weaving of fibers, punching and extrusion of plastic sheets or the welding of cross-laid synthetic elements. Depending on the raw material and the production process geosynthetics can be divided into several types depending on their inherent mechanical characteristics and consequently appropriate application fields. Their main characteristics are tensile strength, tensile stiffness and their stress-strain-performance with special regard to the long term creep behavior; usually documented in ‘Isochrones Curves’. Further general information can be found in SVG (2003) or CUR 234 (2012), EBGEO (2010).

2.2 Guidelines

In Europe all geotechnical structures have to fulfil the requirements and regulations of EN 1997 ‘Eurocode 7 – Geotechnical Design” (EC 7). Since the EC 7 does not include the normative regulations and recommendations for geotechnical structures using geosynthetics several different guidelines have been published in the European countries like France, Netherlands and United Kingdom. In Scandinavia the Nordic Geotechnical Societies have been developed the ‘Nordic Guidelines for Reinforced Soils and Fills’ (NG) in 2003. The latest revision has been published in 2005. The previous versions of ‘Code of Practice for Strengthened / Reinforced Soils and other Fills’ (BS 8006, British Standard Institute 2010) in United Kingdom and ‘Recommendation for Design and Analysis of Earth Structures using Geosynthetics’ (EBGEO, German Geotechnical Society, 2010) in Germany have been developed in the 80s and 90s of the last century. As can be seen in Table 1 these three guidelines deal in total with nine different geosynthetic applications. The main geotechnical applications being Embankments on Soft Soil, Retaining Structures and Reinforced Earth Structures over Point or Linear Bearing Elements are focussed upon in all of the three referenced guidelines. Only the Nordic guideline deals with information about the design and the use of Soil Nailing. Similarly for the particular applications of Reinforced Foundation Pads, Transport Routes and Geosynthetic Encased Columns these are only described in EBGEO.

Table 1: Applications regulated in the guidelines

<table>
<tr><th></th><th>NG</th><th colspan="2">BS</th><th>EBGEO</th></tr>
<tr><td>Embankment on Soft Soil</td><td>x</td><td colspan="2">x</td><td>x</td></tr>
<tr><td>Reinforced Foundation Pads</td><td>-</td><td colspan="2">-</td><td>x</td></tr>
<tr><td>Transport Routes</td><td>-</td><td colspan="2">-</td><td>x</td></tr>
<tr><td rowspan="2">Retaining Structures</td><td rowspan="2">x</td><td>Walls</td><td>x</td><td rowspan="2">x</td></tr>
<tr><td>Slopes</td><td>x</td></tr>
<tr><td>Landfill Engineering</td><td>-</td><td colspan="2">-</td><td>x</td></tr>
<tr><td>Reinfoced Earth Structures over Point or Linear Bearing Elements</td><td>x</td><td colspan="2">x</td><td>x</td></tr>
<tr><td>Foundation Systems using Geosynthetic Encased Columns</td><td>-</td><td colspan="2">-</td><td>x</td></tr>
<tr><td>Overbridging Systems in Areas Prone to Subsidence</td><td>-</td><td colspan="2">x</td><td>x</td></tr>
<tr><td>Soil Nailing</td><td>x</td><td colspan="2">-</td><td>-</td></tr>
</table>

Besides the different applications the guides give information about geosynthetic raw materials and other construction materials as well as their recommended testing procedures.

The design strength estimation of geotextiles is a key issue of guidelines dealing with geosynthetics and is performed differently according to the Scandinavian, British or German guideline and is detailed therein.

Common to all these codes is that the tensile short term strength has to be reduced for the design due to the influence of creep, installation damage, weathering or biological and chemical degradation, for seams and joints and lastly dynamic loads. Depending on the National Annex of each country a partial safety factor has to be considered additionally.

The design strength of a geotextile X_d (kN/m) pursuant the Nordic Guidelines is estimated using equation 1, where X_k (kN/m) is the characteristic short term tensile force in the geogrid. All reduction and the partial safety factors are described in Table 2.

$$X_d = \frac{\eta_1 \cdot \eta_2 \cdot \eta_3 \cdot X_k}{\gamma_M} \qquad (1)$$

Table 2: Reduction and Partial Safety Factors

Reduction and Partial Safety Factors	NG	BS	EBGEO
Creep	$\eta_1 = 1/F_{cr}$	RF_{CR}	A_1
Installation Damage	$\eta_2 = 1/F_{id}$	RF_{ID}	A_2
Biological&chemical degradation	$\eta_3 = 1/F_{nv}$	RF_{CH}	A_4
Weathering	-	RF_W	-
Processing (Seams etc.)	-	-	A_3
Dynamic Load	-	-	A_5
Material Safety Factor	γ_M	f_m	γ_M
Partial Safety Factor for Extrapolation		f_s	

According to British Standard the design strength is estimated by using equation 2 and 3. T_{char} (kN/m) is the characteristic short term tensile force in the geogrid.

$$T_d = \frac{\frac{T_{Char}}{RF_{CR}}}{f_m} \qquad (2)$$

$$f_m = RF_{ID} \cdot RF_{CH} \cdot RF_W \cdot f_s \qquad (3)$$

The design tensile force $R_{b,d}$ (kN/m) in accordance with EBGEO is derived by reducing the characteristic short term strength $Rb,k0$ (kN/m) by the partial safety factors described in Table 2.

$$R_{b,d} = \frac{R_{b,k0}}{A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_5} \cdot \frac{1}{\gamma_M} \qquad (4)$$

Detailed explanations of the reduction factors and their derivation based on ISO/TR 20432:2007 'Guidelines for the determination of the long-term strength of geosynthetics for soil reinforcement' can be found in the Dutch report 'Durability of Geosynthetics' (CUR 243, 2012).
More information about the design principles of GRS can be seen in Section 3.2.

2.3 Geosynthetic reinforced retaining structures

One of the most important applications of geosynthetics are geosynthetic reinforced retaining structures (GRS). These structures are used to stabilize slopes, to construct steep slopes as well as vertical walls and are built by vertically stacking single pads consisting of geogrids and compacted granular soil material. Previously heights up to 41 m have been realised. In order to achieve best GRS performance the use of a geogrid is recommended since its open mesh apertures favour a robust interaction between granular soil and geosynthetic reinforcement.
The numerous methods which can be utilised in the construction of such structures results in a wide variety of reinforcement arrangements and associated facing detailing. This latter matter is very important as it has a direct impact on a structures durability against UV radiation, fire and vandalism. For steepened slopes with an inclination up to 45° the face can be covered with 3D synthetic erosion protection matting or biodegradable, pre-seeded vegetation mats to ensure a successful 'greening' of the slope in the form of sown grasses. Another alternative being the direct application of 'hydro seed' mulch. All successful slope surface vegetation depends greatly on the climate and seasonal exposure of the slope and vegetation in question. Besides these so called green facings the GRS face can be constructed with other materials such as; stone or concrete blocks and panels, full or half gabion baskets filled with rocks.
The most common construction method used is the 'Wrap Around' method whereby the soil fill material is placed on top of a horizontal geogrid layer and is compacted in lifts of max. 0.30 m. The geogrid tail which remains protruding from the front edge of the fill material is then wrapped upwards and back on itself over the top of the compacted fill lift and anchored under the next layer of compacted fill to be placed. Typically such wrap around lifts are between 0.3 m to 0.6 m high. A mobile or a lost formwork (e.g. bent steel meshes) assists in forming a regular and tidy lift profile. GRS structures can generally be built without any special construction equipment, and can therefore be considered as suitable low technology systems. Their adaptability during construction and overall flexible nature enables them to be readily suited to a wide variety of applications and geometries. By virtue of their distinct

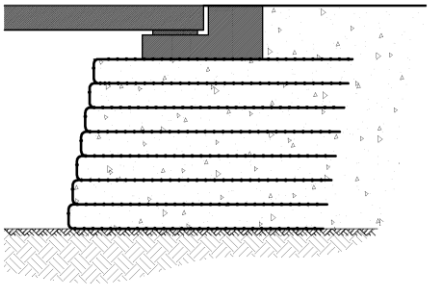

Figure 1 GRS as Bridge Abutment Foundation

Figure 2 Highway A 74 Venlo, Netherland

inherent ductility faced GRS structures performed very favourably during numerous earthquake events in Japan (Tatsuoka et. al., 1998) as well as under seismic load in laboratory tests (see Ling et al., 2013).

Furthermore a GRS is suited to carry high loads (see section 3.2). Especially for this reason the GRS is an attractive alternative to common bridge abutment construction methods.

3 GEOSYNTHETIC REINFORCED BRIDGE ABUTMENTS

3.1 Construction Methods

Geosynthetic reinforced bridge abutments have already become an established construction technique in e.g. Netherlands or Japan that allows a number of construction possibilities, as described.

A bridge superstructure can be founded directly on top of the GRS as performed for the Highway A 74 in the Netherlands (see Figures 1 & 2). The load of the bridge superstructure and traffic is fully carried by the GRS and transferred into the subsoil. The successfully design, construction and long term performance of these types of bridge abutments require a sufficient bearing capacity of the subsoils. Deformation tendencies in the bridge abutment resulting from subsoil settlements can endanger the durability of the rigid elements of the bridge and therefore have to be excluded. The reinforced soil body itself is usually not prone to failure caused by vertical deformations. For the Dutch bridge abutment shown in Figure 1 the potential subsoil settlements caused by loading from the bridge superstructure and live motorway traffic have been additionally allowed for by using a preload performed with concrete blocks placed on top of the GRS structure to simulate the live loadings.

Settlements originating from within the reinforced soil body itself can be minimized by the use of high-quality well graded filling soil with careful compaction in uniform vertical layers. In general the occurrence of these types of settlement is limited largely to the construction phase and can therefore be compensated for easily at this time.

Differential settlements of the bridge abutment and the bridge approach embankments are not expected using this ‘pre-load’ construction method. Any such surface imperfections and cracks due to

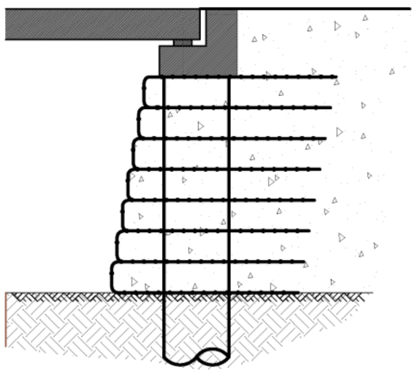

Figure 3 Combination of GRS and deep foundation

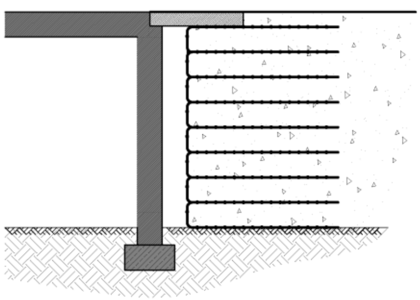

Figure 4 GRS working as Earth Pressure Relief Structure

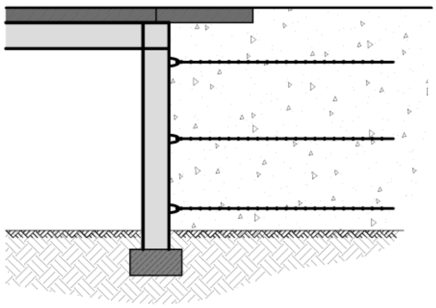

Figure 5 GRS built in soldier beam method

Figure 6, Temporary GRS in Switzerland using locally Fill Material and Soldier Beam Method

differential settlements between the bridge abutment and bridge superstructure may well effect the drive quality and long term durability. For these reasons there always needs to be careful consideration of such serviceability criteria during the design process.

In case of very large bridge spans or very strict settlement requirements a combination of a GRS and deep foundations is an advantageous construction alternative. As can be seen in Figure 3 the loads can be transferred down to a bearing stratum by the use of rigid piles. By using this technique both primary and secondary settlements are almost excluded. In general and especially in this combined bridge abutment construction method the GRS enables the construction of steep side slopes replacing standard reinforced concrete wing walls and thereby also reducing the embankment footprint space requirement.

Figure 4 shows a diagram of a geosynthetic reinforced earth block working as an earth pressure relief wall. The elements of the bridge superstructure and the GRS are not connected but decoupled with a void between them. The bridge structure is therefore not laterally loaded by any earth pressure from the approach embankment fill material. Consequently the dimensions and reinforcement of the (concrete) bridge superstructure and associated foundations can be reduced thereby reducing the overall material costs. Furthermore several special GRS types have been developed, with particular reference to unique individual requirements. Examples of this are shown by in Figures 5 and 6 which illustrate a GRS application in Switzerland where temporary Soldier Beam Walls acting as bridge abutments were constructed and laterally restrained using geosynthetic reinforcement elements. This makeshift bridge enabled the crossing of a railway line and road.

Due to the short installation time of these temporary structures the operation of the railway and road route was ensured. The use of large, locally sourced boulders reduced both the material transport costs and due to their high quality the required tensile strength of the geosynthetic reinforcement.

In summary, depending on the individual project requirements such as load carrying capacity, settlement criteria or even scenic and aesthetic considerations the flexibility and diversity offered by GRS solutions can ensure that a satisfactory solution can almost always be selected.

3.2 Large Scale Test

Many geosynthetic reinforced bridge abutments are already constructed in the Netherlands however prior to this trend full

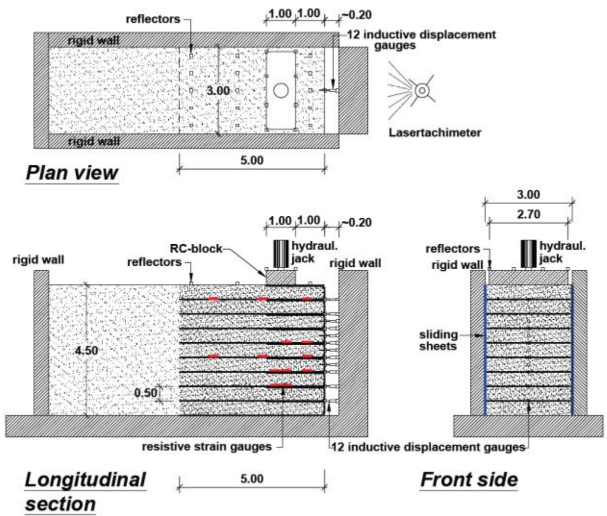

Figure 7 Test wall and measurement equipment, Alexiew and Detert (2008)

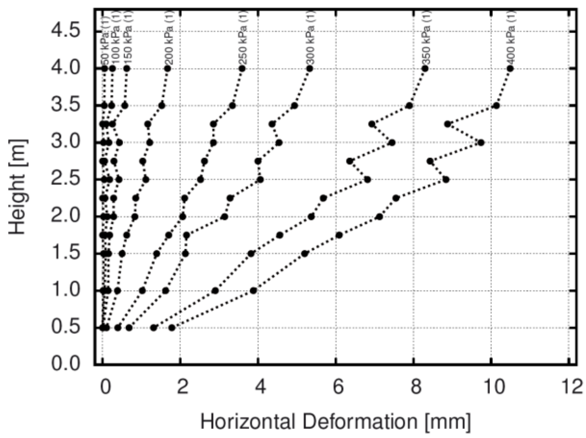

Figure 8 Measured Horizontal Deformation, Test 1

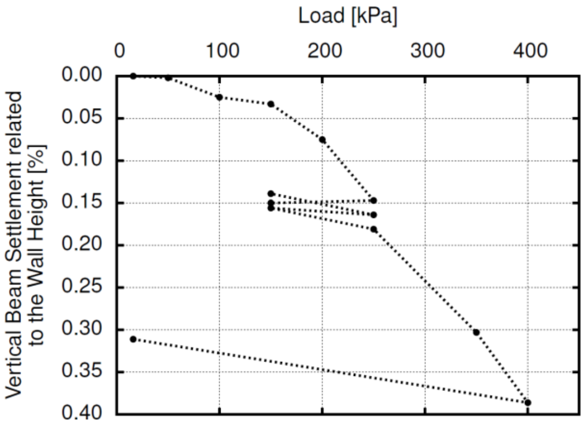

Figure 9 Measured Vertical Beam Settlements, Test 1

scale testing of the concept was carried out to look at the behaviour, stability and deformation of these types of construction (see Alexiew and Detert, 2008).

The experimental concept had been used before for investigations of integral frame bridges and their interaction with GRS abutments (see Plötzl and Naumann, 2005). For the full scale research project referenced *Alexiew and Detert, 2008* a 4.5 m high GRS vertical wall was constructed with nine layers of high strength geogrids made from the raw material PVA. The geogrids had a length of 5.0 m and were installed with a vertical lift height of 0.5 m (see Figure 7), with a 'wrap around' front face detail. The fill material was well graded and was determined to have an angle of friction between 40° and 45° in its compacted, at rest, state.

On top of the GRS structure a RC-block (width 1.0 m, distance form GRS face 1.0 m), served to simulated a typical bridge bank seat foundation beam and was loaded via a hydraulic jack arrangement. The capacity of the hydraulic jack was limited to 600 kPa. However this capacity sufficiently exceeded the typical bridge superstructure bank seat loads of around 200-250 kPa. by a factor of three.

A comprehensive measurement system was installed both within the reinforced soil block and externally to monitor the front face deflections. The use of strain gauges and displacement transducers can be seen in Figure 7.

The test procedure was divided into two parts: firstly load of of 400 kPa was applied to the test structure, then the structure was relieved and afterward a second load of 600 kPa was applied to study the structural deformation as it neared its theoretical failure loading.

As a result the RC-block settlements and the horizontal deformation of the wrapped around facing over the magnitude of the applied loads was visualized in the Figure 8 and Figure 9. The measured settlement under a max. load of 400 kPa was 18 mm which equates to 0.4% related to the GRS height (see Figure 9). It is considered that the initial settlement which occurred in the upper part of the wall during load steps 0 kPa – 200 kPa was most probably caused by additional micro compaction of the fill material, which had been compacted to 95% maximum dry density during construction.

The maximum horizontal deformation measured by the top of 12 deformation gauges was 10 mm (see Figure 9).

During the second part of the test cracks in the RC-block were observed under a load of 500 kPa. Similarly a fissuring in the reinforced earth block was observed to commence around a loading of > 500 kPa. The results of these large scale tests demonstrated the sufficient stability and serviceability of a GRS working as bridge abutment with inherent safety reserves for normal superstructure and traffic loads as well as even higher loads.

3.3 *Geotechnical Design*

As mentioned previously the guidelines from the United Kingdom, Scandinavia and Germany all include information about the design and construction of GRS.

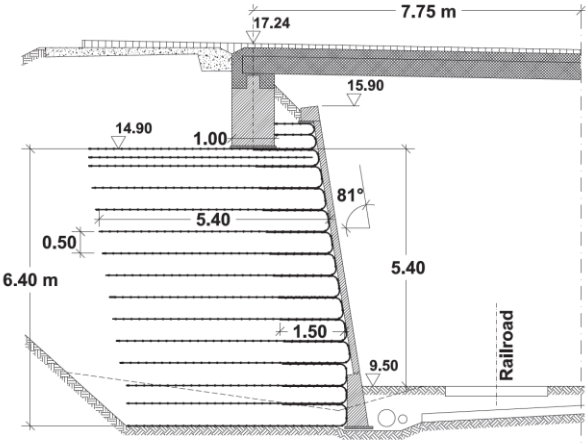

Figure 10 Cross Section, Bridge Abutment Ullerslev

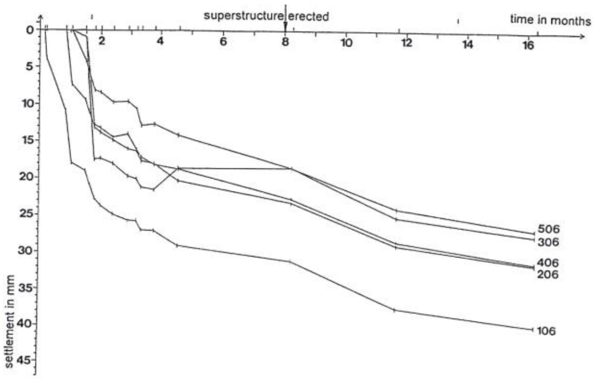

Figure 11 Measured Settlements, Kirschner and Hermansen (1994)

As European geotechnical guidelines they have to fulfil the requirements of the EC 7 and therefore are based on the partial safety factor concepts. Consequently driving forces are increased and resisting forces are decreased by partial safety factors. Those are defined in the National Annexes of each European Country.

Furthermore the guidelines coincide in holding the Ultimate Limit State (ULS, structural and geotechnical failure) and Serviceability Limit State (SLS, intolerable deformations) principles. The therein mentioned typical ULS failure modes for GRS are Pull-out, Rupture of Reinforcement, Internal and Global Slope Stability and Failure of the Facing. Sliding, Bearing Capacity and Settlements have to be considered in the SLS condition.

In conformity with EBGEO the regulations given in DIN 4084 (2009) are also valid for a GRS. Hence slip surfaces cutting the reinforcement layer (internal), not cutting a reinforcement layer at all (global) and slip surfaces cutting at least one reinforcement layer (compound) have to be analysed by using the methods of e.g. Bishop, Janbu or Vertical Slice Method. The same modes have to be analysed in accordance with the Nordic Guidelines. In contrast the British Standard pursues the Coherent Gravity Method and Tie-Back-Wedge method in three different load cases for the internal stability analysis.

Detailed information about the design principles of British Standard, EBGEO and the French Guideline as well as a design comparison of a 7 m high wall can be found in Horgan et al (2014).

3.4 Long Term Behaviour

In 1991 the construction of geosynthetic reinforced walls working as bridge abutments over the Nyborg-Fredericia main railway line in Ullerslev was instructed by the Danish State Railways (DSB) and firstly reported in Kirschner and Hermansen (1994).

Due to the subsoil which was described to be glacial clays DSB was searching for a bridge abutment solution which is not vulnerable to settlements. Nowadays it is usually recommended that a preload equal to or higher than the anticipated total service life load is applied to induce any settlements during the GRS construction as described above (Figure 2) for the Dutch bridge abutment at motorway A 74. However in the 1991 Ullerslev project the settlements were supposed to occur during the service life and therefore a geosynthetic reinforced bridge abutment was preferred due to its ductile and flexible deformation behavior. The aforementioned deformation behavior of the GRS causing uniform settlements of the abutment and the bridge approach (see section 3.1) was exploited in order to increase the durability in terms of ultimate and serviceability limit state of the entire bridge structure.

The Ullerslev bridge abutment (see Figure 10) is built as shown before in Figure 1, viz. the GRS is directly loaded by the load of the bridge superstructure and the traffic load by the use of a concrete block foundation.

The GRS is inclined by an angle of 81° and built using wrapped around geogrids with a vertical distance of 0.50 m. Below the concrete block the layer distance is decreased in order to optimize the load transfer into the 5.4 m long reinforcing geogrids. Those have an estimated required short term strength of 110 kN/m. In Figure 12 the bridge is displayed shortly after the erection of the GRS and installation of the bridge superstructure.

As described in Kirschner und Hermansen (1994) the northern abutment was equipped with measurement points allowing the determination of vertical and horizontal deformations. The vertical settlements during the time span from December 1991 to April 1993 are shown in Figure 11 in five central and vertical orientated measurement points. Whilst the GRS was being constructed the maximum settlements of 30 mm were recorded at the bottom of the structure mainly caused by subsoil settlements. With the addition of the bridge super structure to the GRS after 8 month measured additional settlements of 10 mm within 16 months were recorded. The internal settlements arising in the reinforced soil body has been measured in a range of 25 mm and 30 mm.

Today the bridge is still in use as can be seen in Figure 13 showing a photograph taken in 2013. Obviously in the meantime the face of the wrap around walls was protected from UV impact, erosion and vandalism by applying a thin shotcrete sheet, although a cover with prefabricated concrete panels was initially designed.

Finally the stability and serviceability of the bridge has been maintained during almost 25 years' service life and the bridge has as resisted well any adverse settlements of the subsoil.

4 SUMMARY

The development of geosynthetic reinforced retaining structures (GRS) and their performance for bridge abutments have been introduced. Due to their multifarious construction and design methods GRS are suitable for many construction projects and can be readily adapted to individually unique project requirements.

Figure 12 Bridge Abutment Ullerslev in 1991

Figure 13 Bridge Abutment Ullerslev in 2013

The geotechnical design for GRS in Europe is based on EC 7 and regulated in National Guidelines dealing with geosynthetics. An overview of the Nordic Guidelines, EBGEO and BS 8006 with regard to the main applications, the design strength estimation and the basis of the geotechnical design of GRS have been presented.

The high vertical load carrying capacity and the deformation behavior under loads up to 650 kPa have been analysed in a large scale test. The vertical and horizontal deformations of the 4.5 m high test wall under typical bridge loads of approx. 250 kPa was measured in a range of millimeters thus substantiating the suitability of GRS for bridge abutments.

After almost 25 years' service life the Danish bridge abutment in Ullerslev was highlighted. With regard to the serviceability and stability these bridge abutments have performed soundly. Due to the ductile deformation behavior of the GRS settlements causing from the clayey subsoil have not restricted the use of the bridge.

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