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Embankment project on soft subsoil with grouted stone columns and geogrids

Un projet de remblai sur le sous-sol mou avec les colonnes en pierre injectés de ciment et geogrids

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ABSTRACT
During the years 1993 to 1995, the 150 year old railway between Berlin and Hamburg was upgraded to allow a speed of 200 km/h and heavy loads. Westwards of Berlin the railway passes for 13 km an area with deposits of soft organic soils. An embankment on grouted stone columns with one layer of geogrid reinforcement was constructed. Shortly after the end of the reconstruction settlements and ballast bed deformations started. For this reason and also due to the general need of further upgrading a second reconstruction stage was planned. Extensive investigations (three-dimensional numerical studies, pull-out and geogrid-geogrid shear tests etc.) were carried out. The final developed cross section is an optimum of system behaviour and constructability. In summer 2003 the entire stretch was rebuilt in only eight weeks and put into operation again. The paper describes the results of the investigations, the design and the construction of the track. In addition first in situ measurement results are given.

RÉSUMÉ
Pendant les années de 1993 à 1995, le chemin de fer qui avait étés construit avant 150 ans entre Berlin et Hambourg a été amélioré pour permettre une vitesse de 200 km/h et de charges lourdes. À l'ouest de Berlin cette voie traverse un secteur avec des dépôts de sols mous organiques sur une distance de 13 kilomètres de long Un remblai sur les colonnes en pierre injectés de ciment et renforcé par une couche des geogrids a été construit. Peu de temps après la fin de la reconstruction, les tassements et les déformations de la couche d'agrégat concassé ont commencé. Pour cette raison ainsi que pour le besoin général d'améliorer la voie, une deuxième étape de reconstruction a été projeté. Des investigations étendues (études numériques tridimensionnels, des essais d'arrachement et cisaillement de géogrilles-géogrilles etc.) ont été effectuées. Finalement la section transversale développée est un optimum d'un system effectif et constructible. Le secteur entier a été reconstruit en seulement huit semaines et a été mis en fonction encore en été 2003. Cet article décrit les résultats des investigations, de la conception et de la construction de la voie. En outre les premières résultats de mesure in situ sont donnés.

1 INTRODUCTION

Designing structures, such as buildings, walls or embankments on soft soil raises several concerns. They are related to bearing capacity failures, intolerable settlements, large lateral pressure and movement, and global or local instability. A variety of techniques may be used to address the above concerns. These include preloading the soft soil, using light-weight fill, soil excavation and replacement, geosynthetic reinforcement and soil improvement techniques.

In recent years a new kind of foundation, the so-called "geosynthetic-reinforced and pile-supported embankment" (GPE) was established (Fig. 1).

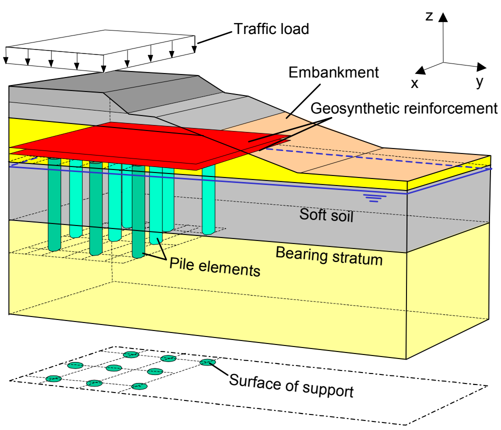

Figure 1. Geosynthetic-reinforced pile-supported embankment

Pile-like foundation elements (e.g. piles, vibro concrete columns, ready-mix mortar vibro columns, walls etc.) are placed in a regular pattern through the soft soil down to a lower load-bearing stratum. Above the pile heads the reinforcement of one or more layers of geosynthetics (mostly geogrids) is placed and above this the embankment is built up.

The stress relief of the soft soil results from an arching effect in the reinforced embankment over the pile heads and a membrane effect of the geosynthetic reinforcement (Fig. 2). A part of the loads is borne directly by the pile-similar elements, another part is first taken over by the geosynthetic reinforcement and afterwards transferred to the pile tops; finally, the loads are transferred down via the piles into the bearing stratum. Some part of the loads could be borne directly by the soft soil if counter pressure can develop (Kempfert et al., 2004).

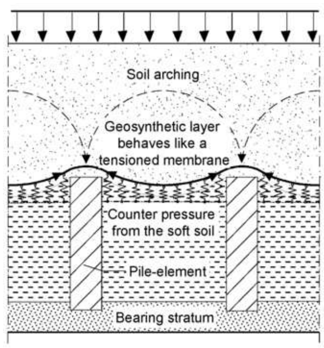

Figure 2. Mechanisms of load transfer

Compared to “conventional” embankment foundations GPE-systems have important advantages from the technical, ecological and financial point of view: no consolidation time is required, there is no import/export of additional embankment soil to accelerate consolidation or to compensate the settlement, practically no additional settlement occurs under traffic etc. The application of GPE-systems is recently increasing in Germany, see Alexiew and Vogel (2001).

The high-speed ICE-link Hamburg-Berlin in Germany is a current example of a geogrid reinforced railway embankment on piles. The old railway was constructed 150 years ago and reconstructed for the first time during the years 1995 and 1996. In the west of Berlin the railway crosses an area with deposits of soft organic soil. An embankment on partially grouted stone columns with one layer of geogrid reinforcement was constructed. After the reconstruction settlements and ballast bed deformations were observed. Therefore and also due to the general need of further upgrading a second reconstruction stage was planned and carried out in 2003. In the run-up to the second reconstruction stage the reasons for the settlements were investigated and a modified embankment was worked out.

The differences between the two GPE-systems will be described shortly with special reference to the fact that the first reconstruction of the railway didn’t lead to a stable system. Moreover, the design of the modified piled embankment, the construction and some monitoring results will be presented.

2 RAILWAY HAMBURG – BERLIN, SECTION PAULINENAUE – FRIESACK

2.1 *Initial Situation*

Westwards of Berlin, at the section between Paulinenaue and Friesack, the railway Hamburg – Berlin (HH-B) passes an area (the so called Havellaendische Luch) with deposits of soft organic soils. The section is 13 km long and the thickness of the soft soil layers varies from 0.5 to 6.5 m. The firm soil layer in the depth consists of dense sand. The ground water level is near the surface.

When the railway was constructed 150 years ago, an embankment with a height of about 2 – 3 m had been carried out (Fig. 3). The old embankment was made up of loose sand.

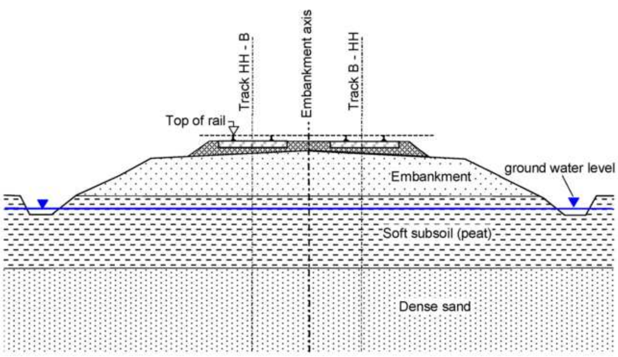

Figure 3. Typical cross-section and soil profile without soil improvement

2.2 *First Reconstruction Stage*

Since the old railway tracks between Paulinenaue and Friesack had experienced considerable settlements in the past it was necessary to improve the bearing capacity of the embankment. During the years 1993 to 1995 the railway was upgraded (1st reconstruction stage) to allow a speed of 200 km/h and heavy loads. The typical cross-section of the 1st reconstruction stage is illustrated in Fig. 4.

It consists of the geogrid reinforced embankment, the partially grouted stone columns, the soft organic soil (peat) and finally the dense sand layer at depth with sufficient bearing capacity. The rails were set on a ballast bed.

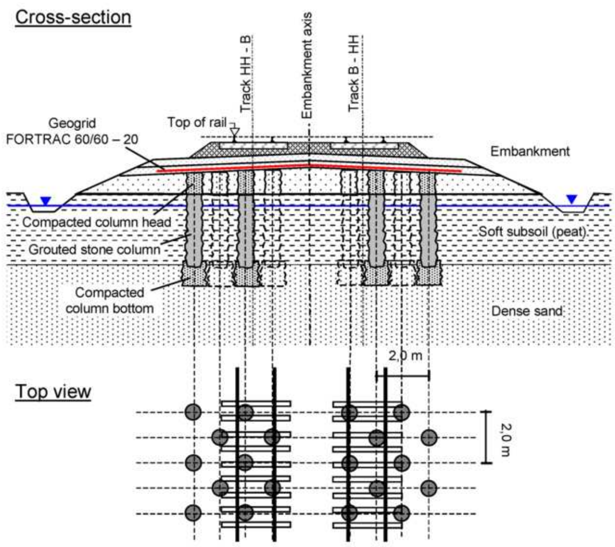

Figure 4. Typical cross-section 1st reconstruction stage

Both tracks were worked on separately to allow at least traffic on one track. Therefore, a temporary sheet pile wall was installed at the middle of the embankment. Then the rails, the ballast bed and the embankment were removed up to a depth of 1m below the old top of the rail. Cemented stone columns with compacted, non cemented column heads and column bases in a triangular pattern and an axial spacing of about 2.0 m were chosen as vertical bearing elements. The columns had a diameter of approx. 0.6 m and were founded in the firm sub-layers. It was planned that the cemented stone columns reach the top of the organic soil layer. On the top of the cemented stone columns, compacted non cemented column heads, consisting of gravel, were placed. Above these a geosynthetic-reinforced bearing layer with a thickness of 0.6 m was laid. The used biaxial geogrid Fortrac 60/60 - 20 had only an ultimate short-term strength of 60 kN/m in both directions and was installed in one layer parallel to the embankment axis. Because of the temporary sheet pile wall no overlapping of the geogrid was possible in the middle of the embankment. Moreover, there were no vertical bearing elements at the area of the embankment axis. The sheet pile wall was removed after completion of the track.

2.3 *Second Reconstruction Stage*

Shortly after the end of the first reconstruction, settlements and ballast bed deformations had occurred again. For this reason and also due to the general need of further upgrading of the track structure for a train speed of 230 km/h, a 2nd reconstruction stage was planned in summer 2001. In the run-up to the 2nd reconstruction stage extensive investigations were carried out.

A part of the track was closed and the embankment was excavated within a 50 m long test field in order to inspect the embankment construction (particularly the status of the geogrid and the cemented stone columns) and the subsoil situation.

Within the test field it was observed that several cemented columns ended below the required height. Only non cemented gravel was found below the top of the organic soil layer (Fig. 5), while the geogrid was completely intact and in a good condition.

Figure 5. Test field and excavated columns with different heights

In addition to the test field, numerical investigations were carried out. The outcome of the investigations was that the current embankment construction doesn’t permit an upgrading of the track structure for a train speed of 230 km/h. Based on the results of the investigations from the test field and the results of the numerical investigations, the modified track structure illustrated in Fig. 6 was recommended to rebuilt the embankment in the test field.

Therefore, the piles were cut and the organic soil was removed down to 3.2 m below the top of the rail (below 3.2 m depth all cemented stone columns were intact). The modified track structure consisted of three layers of high-strength geogrid, which were connected to a permanent sheet pile wall at the embankment axis.

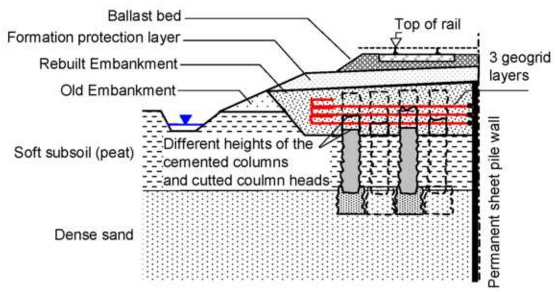

Figure 6. Rebuilt test field, modified double track structure

The rebuilt section had been instrumented with inclinometers and geophones (acceleration gauges) for monitoring the deformation behaviour and the dynamic behaviour of the structure and was put in operation again. The performance of the system was tested during 15 months and its functionality was confirmed, see Tost (2003).

The final double track structure, which was carried out in summer 2003 is illustrated in Fig. 7. Some more modifications were implemented. The flat optimised embankment has a height of 2 – 3 m. The lowest working plane was raised from –3.2 m up to –2.7 m below the top of the rail to prevent operations below the ground water level and because ground water lowering was not allowed.

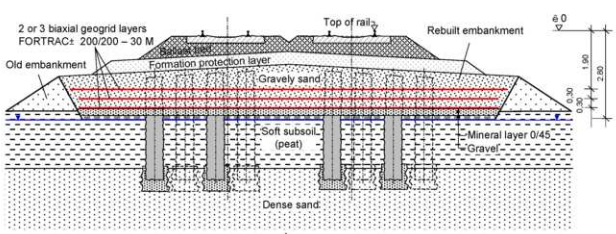

Figure 7. Typical cross-section 2nd reconstruction stage

The old embankment was removed down to this depth, afterwards the columns were cut and the organic soil between the column heads was excavated up to –2.8 m depth below the top of the rail. The area between the column heads was filled up with gravel and above this a 0.2 m thick protective mineral layer was rebuilt. On top of the protective layer two or three geogrid layers were placed at vertical spacing of 0.3 m. Based on the structural analyses biaxial PVA-geogrids (FORTRAC± 200/200 – 30M) with optimised mesh size, high-moduli and low-creep were selected, having an ultimate tensile strength of 200 kN/m in longitudinal and transverse direction and an ultimate strain of about only 5 %. The mineral layers between the geogrids consisted of gravely sand. Finally, the remaining embankment with a 0.4 m thick protection layer was reconstructed and the rails were set on a ballast bed.

This last modified double track structure was the result of further extensive investigations. The bearing and deformation behaviour of the entire system was investigated by three-dimensional numerical studies, see Kempfert and Heitz (2003). Due to the change of the working plane from –3.2 m to –2.7 m several columns were expected to be non cemented in the area of the column head after removing the embankment (like in the test field). Therefore, within the numerical studies a part of the columns were assumed to have defects in the area of the column head. Seven possible defect scenarios were worked out. The results of the three-dimensional numerical studies were compared to the undamaged case (all columns heads intact and cemented). The conclusion was that in the undamaged case two layers of geogrid would fulfill the requirements concerning the serviceability ultimate state. In five out of seven damage scenarios an additional geogrid layer was necessary.

Pull-out tests and geogrid-geogrid shear tests had been carried out to investigate the interaction behaviour between the geosynthetic reinforcement and the embankment soil, see Kempfert and Heitz (2003). In Fig. 8 the shear box and some pull-out test-results are shown.

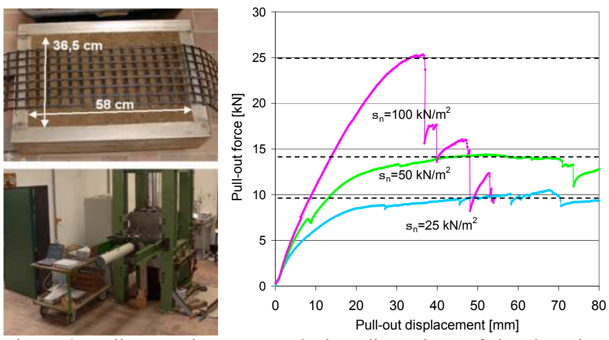

Figure 8. Pull-out resistance test device, dimensions of the shear box and test results (pull-out force versus displacement for different normal stresses)

Both in the pull-out and in the shear tests high coefficients of interaction were registered for the tested FORTRAC± geogrid. This allowed to reduce the overlaps and to avoid any wrapping-back in the anchoring zones at the edges of the system (Fig. 7) thus saving costs and installation time.

The dimensioning of the geogrid was based on the new developed German recommendation “Chapter 6.9 - Reinforced soil structures above point- or line shaped bearing elements” (Empfehlung 6.9, 2002). The recommended theoretical model describes the stress-distribution in the embankment and the membrane effect of the geosynthetic reinforcement. The analytical model for the stress-distribution in the embankment is based on the lower bound theorem of the plasticity theory. To predict the stresses in the reinforcement an analytical model is applied based on the theory of elastically embedded membranes (Zaeske, 2001), see Fig. 9.

This new design method represents a new state of the art. It is believed to be more precise and realistic than the “older” procedures available (e.g. BS 8006, 1995).

In addition, recommendations regarding embankment geometry, soils, reinforcement and construction are presented in “Chapter 6.9” based on German and international experience and experimental results, see Kempfert et al. (2004). This new findings were considered in the second reconstruction stage.

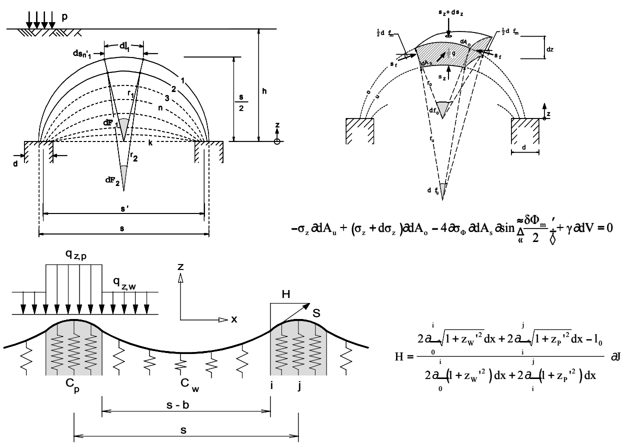

Fig. 9. New soil arching and membrane approach (Zaeske, 2001)

The final cross-section is an optimal combination of system behaviour and easiness of construction. The high-moduli low-creep geogrids control the serviceability easily. The layers are installed as deep as possible near the column tops in order to achieve maximum efficiency of reinforcement. For the contractor it was easy to switch from two to three layers in sections with missed column heads, no wrapping-back was required for anchoring (see above) and the flexible grids used have no “roll memory” thus allowing an easy flat and even installation. Only a 0.2 m thin protective mineral layer is implemented between the lowest reinforcement and the column heads due to their extreme roughness after cutting. Furthermore, no pile sheet wall was required. The biaxial geogrid layers were installed transverse to the embankment axis over the whole embankment width.

3 CONSTRUCTION OF THE TRACK

Between July and September 2003 the entire 13 km long stretch was rebuilt in only 76 days. Both tracks were closed during this period. The works ran around the clock, the peak-period demand of construction workers was 450. All in all 37000 partly grouted stone columns were excavated, investigated and cut. Fig. 10 illustrates the cutting of a pile head and the removed embankment.

Fig. 10. Cutting the pile heads (left) and removed embankment (right)

The removal of the old embankment was done in sections. Simultaneously to the excavation of the grouted stone columns, their status were examined and documented. Depending on the number of intact column heads available at –2.70 m below rail, two or three geogrid layers were installed according to the numerical simulations mentioned earlier. The track was put into operation again in September 2003.

4 MONITORING RESULTS

For verification of the design and certification of stability and serviceability, a monitoring program was installed. It includes three comprehensively instrumented measurement cross-sections. A large quantity of vertical and horizontal inclinometers and geophones had been installed. Additionally, the settlements of the rails had been measured.

Meanwhile, measurements are running for about 12 months under traffic. The long-term monitoring has confirmed the stability and serviceability of the structure. Fig. 11 shows typical results for the settlements at different levels.

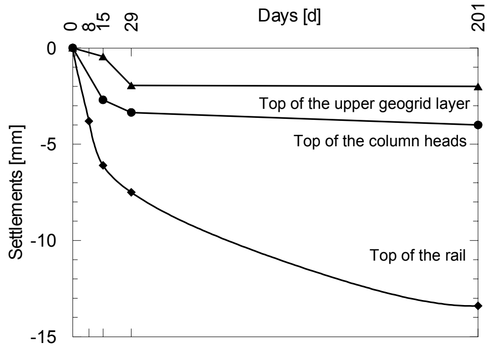

Fig. 11. Monitoring cross-section 1, Track Hamburg – Berlin; vertical deformations versus time

5 CONCLUSION

Flat geogrid-reinforced railroad embankments can be built successfully also for the purpose of reconstruction and upgrading. Careful design considering different supporting conditions and constellations, and the selection of appropriate optimised geogrids were the key issues for that project. The system has proved to perform well regarding both bearing capacity and serviceability.

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