GEOGRID REINFORCED RAILWAY EMBANKMENT ON PILES RAILWAY HAMBURG – BERLIN, GERMANY

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ABSTRACT - The application of reinforced and pile-supported embankments is recently growing in Germany. A current example is the high-speed ICE-link Hamburg-Berlin. West of Berlin the railway passes through an area with deposits of soft organic soils. In the first reconstruction of the track an embankment on grouted stone columns with one geogrid layer 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 for further upgrading a second reconstruction stage was planned. Extensive investigations (three-dimensional numerical studies, pull-out and geogrid-geogrid shear tests) 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 in operation again. The paper describes the results of the investigations, the design and the construction of the track. Furthermore, first in situ measurement results are given.

1 INTRODUCTION

Soil improvement and reinforcement techniques have undergone a significant development during the last decade, especially as a result of the increasing need to construct on soft ground providing economical solutions. 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). Pile elements (e.g. concrete piles, cemented stone 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.

In areas with soft subsoil embankments supported by piles or columns and a horizontal geogrid reinforcement on top of the piles have important advantages compared to “conventional” embankment foundation from the technical, ecological and financial point of view. The application of such solutions is recently growing in Germany, see Alexiew and Vogel (2001).

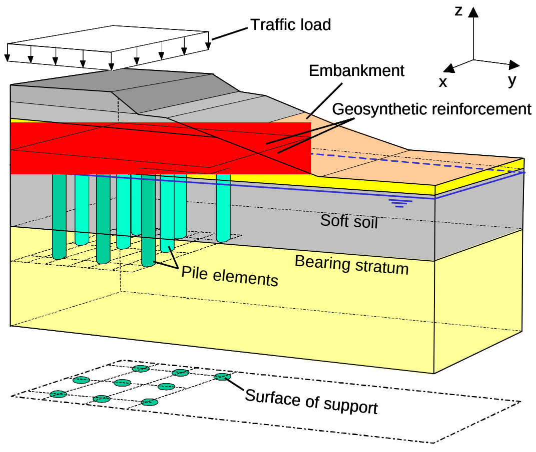

Fig. 1. Geosynthetic-reinforced pile-supported embankment

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 region Paulinenaue and Friesack the railway crosses a longer area of soft subsoil with a thickness varying from 0,5 to 6,5 m. In this region the soft subsoil was improved with partially grouted stone columns. Above this a geosynthetic-reinforced embankment was rebuilt. After the reconstruction settlements and ballast bed deformations were observed. Therefore and also due to the general need for further upgrading, a second reconstruction stage was planned and carried out in 2003. For the second reconstruction stage the construction of the reinforced embankment was modified. 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 led to a stable system. Moreover the design of the modified reinforced and pile supported embankment, the construction and some monitoring results will be presented shortly.

2 GENERAL PRINCIPLES AND GERMAN EBGEO

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. Due to the higher stiffness of the piles in relation to the surrounding soft soil, the vertical stresses from the embankment are concentrated on the piles, simultaneously soil arching develops as a result of differential settlements between the stiff pile heads and the surrounded soft soil. The 3D-arches span the soft soil and the applied load is transferred onto the piles and then to the bearing stratum (Fig. 2).

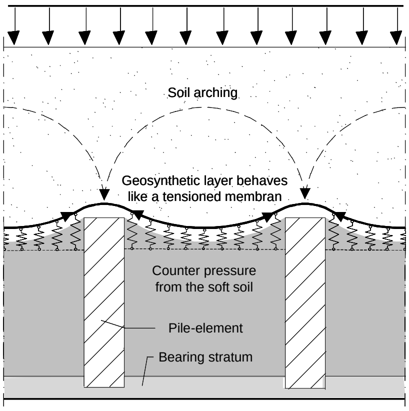

Fig. 2. Mechanisms of load transfer and interaction

In 2003 a new developed design procedure was introduced in the German recommendation "Chapter 6.9 – Reinforced soil structures above point- or line shaped bearing elements" (Empfehlung 6.9 (2003)) and released as a draft to the public. Chapter 6.9 will soon be a part of the new edition of the EBGEO. (Note "EBGEO": The aim of these recommendations is to harmonize and further develop the methods, according to which reinforced earth structures are designed, calculated and carried out. Since 1989, these have been drawn up by the working group for earth reinforcements of the German Society for Geotechnical Engineering under the name EBGEO and are similar to a set of standards. The recommendations help in designing and calculating reinforced earth structures, unifying approaches to loads and methods of calculation and improve the profitability of reinforced earth structures.)

In Chapter 6.9 recommendations regarding embankment geometry, soils, reinforcement and construction are presented based on German and international experiences and experimental results. For further informations see Kempfert et al. (2004).

This new findings were considered in the second reconstruction stage of the high-speed ICE-link Hamburg-Berlin.

3 RAILWAY HAMBURG – BERLIN, SECTION PAULINENAUE – FRIESACK

3.1 Initial Situation

Westwards of Berlin, at the section between Paulinenaue and Friesack, the railway Hamburg – Berlin passes through an area (the so called Havellaendische Luch) with deposits of soft organic soils. The section is 13 km long and the soft soil layers have a thickness of up to 6,5 m. The firm soil layer in depth consists of dense sand. The ground water level reaches the fill toe.

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

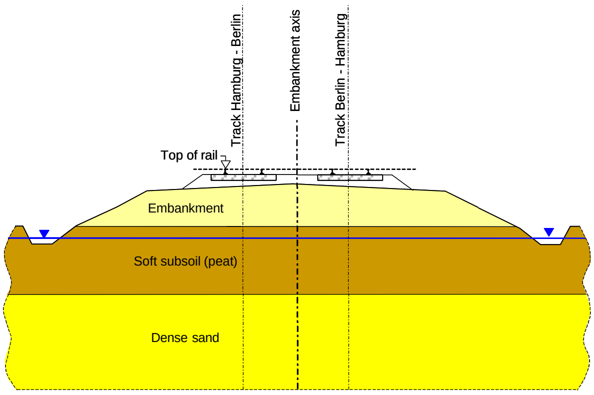

Fig. 3. Typical cross-section and soil profile without soil improvement

3.2 First Reconstruction Stage

Since the old railway tracks had suffered considerable settlements in the past between the section Paulinenaue and Friesack it was necessary to improve the bearing capacity of the embankment. During the years 1993 to 1995, the railway between Hamburg and Berlin 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.

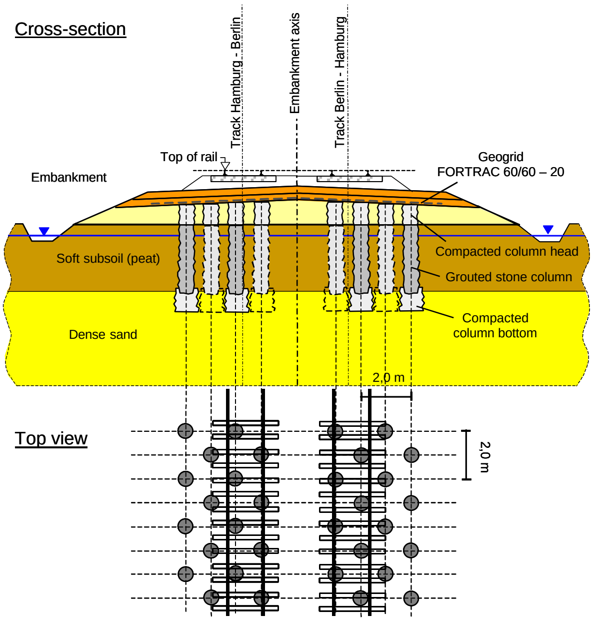

Fig. 4. Typical cross-section 1st reconstruction stage

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

Both tracks were treated separately to allow a smooth flow of traffic. 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 1 m below the old top of the rail. As vertical bearing elements, 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. 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 column, a compacted and non cemented column head consisting of gravel was placed, above which 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 at 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.

3.3 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 for further upgrading 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 (Fig. 5).

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. 6), while the geogrid was undamaged and in a good condition.

Fig. 5. Temporary sheet pile walls and excavated embankment in the test field

Fig. 6. 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 not 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. 7 was recommended to rebuilt the embankment in the test field.

Therefore, the piles were cut and the organic soil was removed up 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.

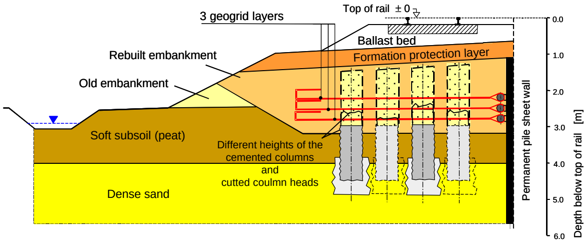

Fig. 7. Rebuilt test field, modified double track structure

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.

The final double track structure which was carried out in summer 2003 is illustrated in Fig. 8. Some more modifications were implemented. The flat optimised embankment has a height of 2 – 3 m. The lowest working plane was heigthened 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.

The old embankment was removed up to this depth, afterwards the piles 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 intervals 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 5 %. The mineral layers between the geogrids consisted of gravely sand. Finally, the remaining embankment with a 0,4 m thick formation 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). Seven possible damage scenarios were tested with the help of numerical calculations. Due to changing 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 (like in the test field) after removing the embankment. Therefore, in the numerical damage scenarios a part of the columns were simulated defect in the area of the column head.

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 2 layers of geogrid would fulfill the requirements concerning the allowed settlements and in 5 out of 7 damage scenarios an additional geogrid layer was necessary. In addition to the numerical studies, 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). Also the required overlapping length was determined.

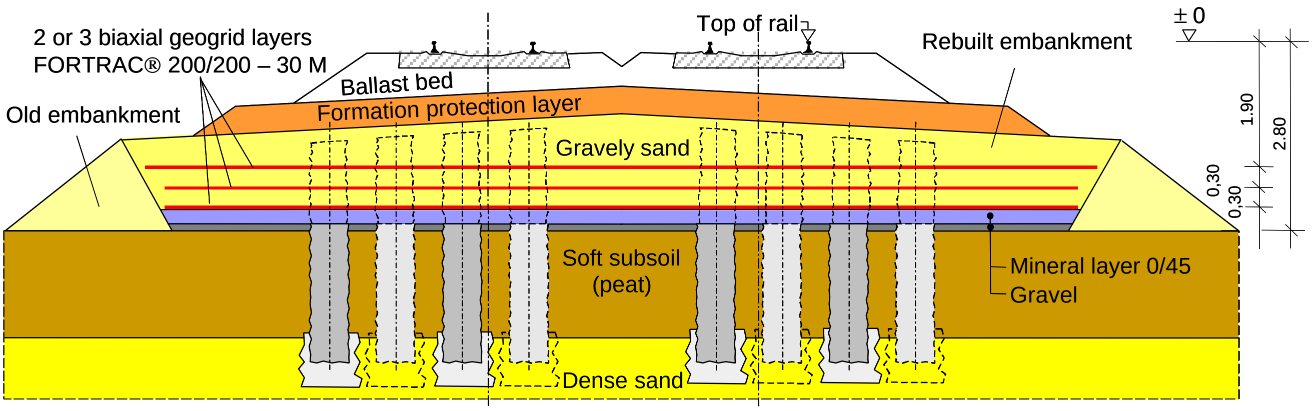

Fig. 8. Typical cross-section 2nd reconstruction stage

In Figs. 9 and Fig. 10 the shear box and some pull-out test-results are illustrated. Because of the large dimensions of the shear box, it was possible to investigate geogrid strips with a width of 24 cm without disturbing influences due to the coarseness of the soil.

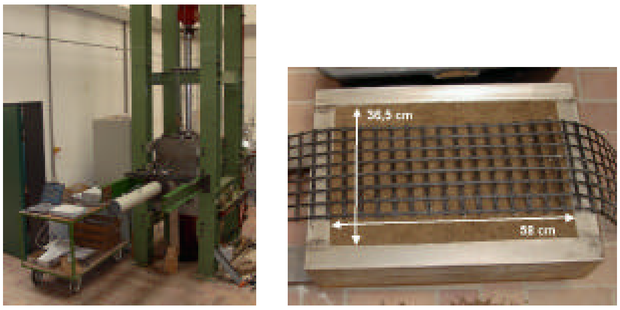

Fig. 9. Pull-out resistance test device and dimensions of the shear box

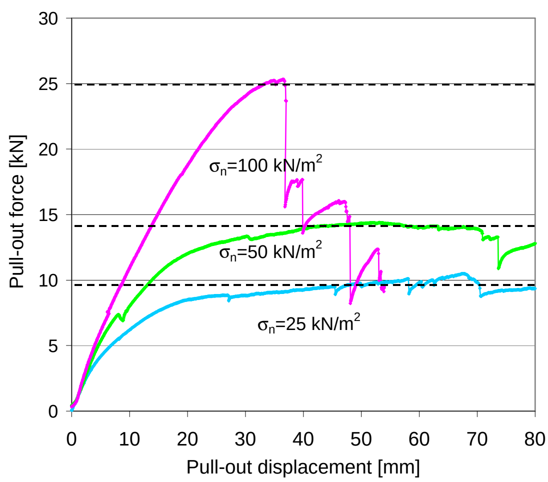

Fig. 10. Test results: Pull-out force versus displacement for different normal stresses

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 (2003)). 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 and results from pretended directions of the stress trajectories in the reinforced soil body. To predict the stresses in the reinforcement, an analytical model is applied based on the theory of elastically embedded membranes (Zaeske 2001). This new analytical 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)). Further information about the German analytical dimensioning procedure are given in Kempfert et al. (2004).

The final cross-section is an optimum solution of system behaviour and easiness of construction. The advantages of the modified track structure compared to the track structure of the 1st reconstruction stage or the rebuilt test field system are the high-moduli geogrids and the small distance between the cemented column heads and the geogrid in order to achieve maximum efficiency of the geosynthetic membrane. Only a 0,2 m thin protective mineral layer is implemented between the lowest reinforcement and the pile heads in order to prevent a structural damage of the reinforcement due to shearing at the edge of the pile heads. Furthermore, no pile sheet wall was required. The geogrid layers were installed transverse to the embankment axis and the whole embankment width.

4 CONSTRUCTION OF THE TRACK

Between July and September 2003 the entire stretch was rebuilt in only 76 days. Therefore, both tracks were closed during this period. The workings were done day and night. All in all 37000 partly grouted stone columns were excavated, investigated and cut. Fig. 11 illustrates the cutting of a pile head.

Fig. 11. Cutting the pile heads

Fig. 12. Removed embankment

The removal of the old embankment was done in 10 m long sections. Simultaneous to the excavation of the grouted stone columns, the status of the columns were examined and documented for each section. For the case the excavated column conditions were similar to a numerical calculated damage scenario, three geogrid layers were built in otherwise, when nearly all columns were intact only two geogrid layers were necessary.

Figures and facts about the reconstruction works:
Removal of the embankment:
- 23 km overhead contact wire,
- 23 km trails in 6 days,
- 45.000 m^3 ballast,
- 115.000 m^3 formation protection layer,
- 185.000 m^3 embankment soil,
- 135.000 m^2 geogrid,
- 60.000 m^3 soft soil (peat),
- 37.000 grouted stone columns were cut.

Reconstruction of the embankment:
- 50.000 ton gravel,
- 85.000 ton protective mineral layer,
- 410.000 m^2 geogrid,
- 400.000 ton embankment soil,
- 130.000 ton formation protection layer,
- 23 km ballast bed, trails and overhead contact wire.

The peak-period demand of construction workers was 450. The track was put in operation again in summer 2003. Results of the extensive measurement program installed at different levels by different gauges are shortly displayed supporting the success of the described concept, design and final system.

5 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.

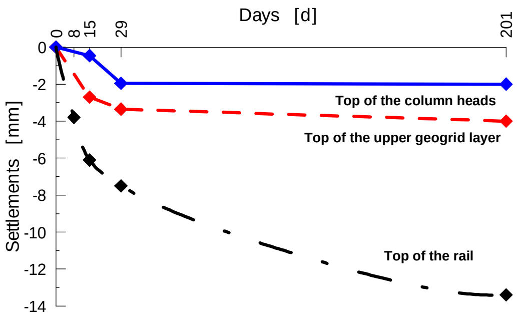

Fig. 13. Monitoring cross-section 1, Track Hamburg – Berlin; vertical deformations versus time

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 since about 8 months under traffic. The long-term monitoring has confirmed the stability and serviceability of the structure. Fig. 13 shows typical results for the settlements at different heights of the monitoring cross-section 1.

6 CONCLUSIONS

The carried out investigations in the run-up of the second reconstruction stage supported that the final GPE-System can provide a stable railway track with a low deformation risk.
The current monitoring results show only low and uniform settlements of the embankment which are in the expected range. This confirms the efficiency of the railway track reconstruction Hamburg-Berlin. The system has proved to perform well regarding both bearing capacity and serviceability.

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