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Railroads on piled embankments in Germany: Milestone projects

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ABSTRACT: Embankments on soft subsoil supported by piles and geogrid reinforcement on top of them have important advantages compared to "conventional" embankment foundation: no consolidation time is required (traffic can start immediately after construction), there is no import/export of additional embankment soil to accelerate consolidation or to compensate the settlement, practically no additional settlement occurs under traffic, the interference with the environment is minimized, etc. The application of such solutions is growing recently in Germany. The most important projects of this type being "milestones" for the German Railways (Deutsche Bahn, DB) with high-strength geogrids are presented, demonstrating the development of experience, materials and acceptance. All structures have been approved by the German Supervising Authorities. Long-term measurement results for the "oldest" project are presented also.

1 INTRODUCTION

Embankments on soft subsoil supported by point-bearing piles or columns have important advantages compared to embankments directly founded on soft soils (today typically embankments with high-strength geotextile in the base to ensure local and overall stability, with or without vertical strip drains to accelerate consolidation): due to the load transfer via the piles/columns into the firm sub-layers the soft subsoil has to carry only marginal additional loads, therefore no consolidation time is required (traffic can start immediately after construction), there is no import/export of additional embankment soil to accelerate consolidation or to compensate the settlement , practically no additional settlement even under traffic occurs if the system is correctly designed, the interference with the environment is minimized, etc.

Generally different alternatives are available when setting the embankment on piles, starting with the oldest solution with a concrete slab on top of them. The cost-benefit analysis today results in most cases not in a RC-slab, but in a solution with one or two layers of horizontal high-strength geosynthetic reinforcement on top of the piles/columns (= the base of embankment), which may have a large pile spacing and small pile caps (or no caps at all).

The use of last mentioned solution is growing recently in Germany. First concepts were analyzed about eight years ago. About seven years ago such systems were designed and then constructed for the first time for the German Railways (Deutsche Bahn, DB) for heavy loads and fast trains, followed by others. High-strength biaxial and uniaxial geogrids from 150 kN/m to 800 kN/m ultimate tensile strength (UTS) have been used successfully. Short- and long-term measurement programs were performed and are still ongoing with positive results.

The most important projects of reinforced embankments on piles/columns with high-strength geogrids for DB are presented, demonstrating the development of systems, materials, technologies and acceptance. DB as owner has very high requirements concerning safety and serviceability. All structures have been finally approved by the German Supervising Authorities also (Federal Railroad Agency, FRA). The most important long-term measurement results for the „oldest" executed project after more than 5 years under traffic are presented also, confirming the long-term stability and serviceability of the system.

2 GENERAL PRINCIPLES

The principle of functioning and dimensioning is based on the fact that, after redistribution of stresses (similar to a 3D-arching) in the point-supported embankment body, the major portion of the stresses is transferred directly to the tops of the columns/piles, while the remaining portion (which would otherwise overstress the soft subsoil between the piles leading to local and/or global failure or unacceptable settlement differences) is absorbed by the membrane-type supporting effect of the horizontal reinforcement (Figure 1).

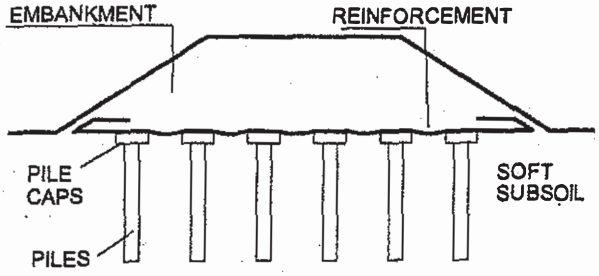

Figure 1. General principles of geosynthetic reinforced embankment on piles/columns.

The German analytical dimensioning procedure being applied with some modifications during the last years is described in Kempfert et al. (1997). It assumes a stress redistribution ("arching") according to Hewlett & Randolph (1988). Thus, it depends on both the embankment and pile geometry and the soil strength. This is one of the most important differences to a popular code, namely to British Standards Institution (BSI) BS 8006:1995 (1995), which (surprisingly) does not take into account the strength (say φ) of the embankment soil. Another difference is that a portion of the upwardly directed reaction stress of the subsoil between the piles may be included in the final equation for reinforcementtension as counter-pressure thus reducing the requireed tensile forces. For that purpose a part of the undrained shear strength c_u (or s_u) of the soft subsoil can be used as described in Kempfert et al. (1997); this is not the case in BS 8006.

Note: assuming an upward reaction stress for the entire design life (which is >100 years for permanent structures in Germany) i.e. reducing the calculated force in the geogrids could be risky, because e. g. a decrease of the ground water level even decades after construction could eliminate the upward counter-pressure due to settlement of subsoil. Flexible geogrids could follow the settlement to some extend "keeping the contact" (which is by the way an important difference to a RC-slab), but the prognosis is very uneasy. Consequently, this assumption of counter-pressure is being analysed/judged by DB for every single project for the post-construction-stage design.

The allowed total strain (short-term & creep) of the geosynthetic reinforcement over the service-life of the structure (>100 years for DB) is being limited by the DB to a maximum of 3% in railway structures, which is definitely a hard restriction on the safer side (e. g. BS 8006 (1995) allows 6%).

Some additional special not only railroad-related issues (e. g. "pile-punching" in extremely low embankments) were discussed in Vogel (1995) and motivated a corresponding research in Germany to analyse and take into account the possible problem; meantime it has been done: in most cases of practical relevance punching is not an issue for stronger reinforced systems.

The spread forces (H-forces) perpendicular to the embankment axis below the slopes near their edges have to be overtaken by the reinforcement (no inclined columns for H-forces!). They can be calculated as described e.g. in British Standards Institution (BSI). BS 8006:1995 (1995) using a simplified approach on the safer side. The total active earth pressure between the crest and the base of the embankment is assigned to the geosynthetic layer perpendicular to the embankment axis, resulting in significant tensile forces. Other more precise procedures performed by the authors result in lower spreading forces.

In the following chapters five "mile stone"-projects for DB of the type mentioned will be shortly described with their most important focal points only. Due to the lack of place some differences in the dimensioning procedures and assumptions in the projects during the years can not be explained in detail herein. Generally, the "German procedure" mentioned above has been used; it is the only one which is being accepted by DB and FRA at the present time. Research and development were and are still ongoing in Germany, based on mathematical analysis (e. g. Alexiew 1996), on the experience today incl. monitoring (e. g. Alexiew & Gartung 1999), and on large-scaled tests (Kempfert et al. 1999). These activities result day by day in a better understanding of the structure's behavior and in optimised design.

3 PROJECT WERDER-BRANDENBURG NEAR BERLIN

This project was not the first one discussed and developed for and with DB (the analyses for the projects described in Chapter 4 herein started earlier), but it was the first one constructed and put into operation.

During the years 1994 to 1995, the one-hundred-year-old railway line between Berlin and Magdeburg was upgraded to withstand a speed of 160 km/h and heavy loads. Soft organic soils were found on parts of the stretch between Werder and Brandenburg. To provide for the foundation of the railway embankment, a conventional total soil replacement was made only in the thinner (about up to 2 m) compressible soil layers. In sections in which the soft soil layers were thicker, a geogrid reinforced embankment on piles was proposed.

At the time of deciding to accept the proposal, DB yet had no experience of geogrid reinforced embankment structures on piles as permanent foundation. The subsoil layers comprise organic soils having a depth from 2 m to more than 20 m and typically c_u-values scattering from 10 kPa to 25 kPa.

Below, loose, uniformly sand is to be found, which transfers to dense sand or boulder clay as depth increases and can then serve as foundation soil for vertical pile loads.

The ground water extends from close to ground surface to a depth of 2 m (Brandl 1994.). The organic soils have a low permeability and a low coefficient of consolidation. Very slender "ductile cast-iron" driven piles with precast 1.0 m x 1.0 m RC-caps on top were used in a square pattern of 1.9 m axially, with total lengths varying from 10 m to 30 m, while soft subsoil thickness varied from 4 m to 20m.

Both tracks were treated separately to allow to keep the traffic going. The respective working track was secured by a temporary sheet pile wall at the middle of the embankment (Figure 2). Three layers of 5 m wide biaxial geogrids were installed to ensure support and load transfer to the pile caps in both directions. The flexible geogrids (Fortrac® R 150/150-30) are made of high-tenacity coated polyester with low creep (important due to the strict long-term deformation limitations), having an ultimate short-term strength (UTS) of 150 kN/m in both directions and a corresponding ultimate strain of about 13%. Some of the layers were jointed in plant by special high-strength seems.

At this time (in 1993-1994), the load bearing performance of the system "embankment soil – geogrids – caps - piles - soft subsoil" could not be described definitively in mathematical terms in a "guaranteed way". Additionally for this project only 3 % total (i. e. short-term plus creep) strain of geogrids were allowed for 120 years design life. No difference was made between (short-term) construction stage, start of traffic and (long-term) operation stage, on the one hand, and the stage-corresponding time-dependent geogrid strains, on the other hand. It was a conservative requirement, resulting in a more or less conservative design.

Very important issues were the QA of geogrids (control of the prescribed mechanical parameters, precision of installation etc.) and the QA of earthwork.

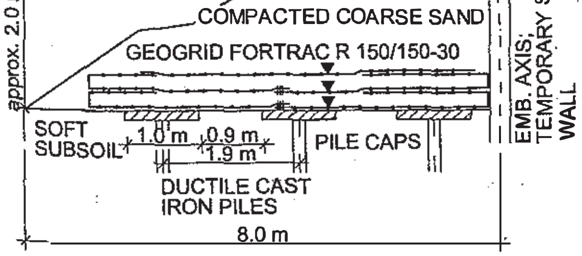

Figure 2. Project Werder-Brandenburg: typical cross-section.

The piled sections are since about six years in operation, being accompanied by an extensive monitoring program (see last chapter herein), and performing better (less maintenance work required) than the stretches founded on common soil replacement, see above. Both materials and structure have been approved by FRA also.

4 PROJECTS SOUTHERN BYPASS STENDAL

The new high-speed rail link Hanover-Berlin for the ICE-trains (Inter City Express), having a speed up to 300 km/h, had to bypass the city of Stendal in 1996 from the south, crossing areas with soft subsoil on two sections (designated as PfA 4.3 and PfA 4.6) of some hundred meters each. The soft clayey layers have a thickness of typically about 6 m to 8 m from the terrain to the firm sub-layers consisting of sandy gravel and gravelly sands. The subsoil strength varied in a wide range from $c_u = 15$ to 25 kPa.

First prelaminary studies and analyses including a geosynthetic-reinforced system on columns started in the early nineties. In both cases a geogrid-reinforced embankment on columns was found to be the optimal solution. Final design was performed more or less parallel to the project Werder-Brandenburg by different teams, but the construction started later. This project was a further step in application of such systems, using them for the foundation of a high-speed link now (300 km/h instead of 160 km/h for Werder-Brandenburg). The rails had to be set on a ballast bed. As vertical bearing elements cemented stone columns without pile caps in a triangular pattern and an axial spacing of about 1.8 m were chosen having a diameter of approx. 0.6 m and being founded in the firm sub-layers. The axial spacing was maximised for using the full column bearing capacity and saving costs. The most important difference between the sections PfA 4.3 and PfA 4.6 was the embankment height being about 2.5 m for PfA 4.3 and about 1.5 m (only!) for PfA 4.6, and the subsoil conditions, which were a bit better for PfA 4.3 despite the c_u-scatter. The allowed total strain of geogrids was limited to 3% for 100 years for this projects also (see Werder-Brandenburg), but in that case this requirement seems to be sound (high-speed-trains!). For PfA 4.3 high-strength flexible uniaxial geogrids Fortrac® R 200/30-30, having an UTS of 200 kN/m in longitudinal direction (machine direction, MD) and an ultimate strain of about 12% were used. For PfA 4.6 the design calculations resulted in two layers of specially produced semi-biaxial geogrids Fortrac® R 400/200-10 with 400 kN/m and 200 kN/m UTS in machine (MD) and cross-machine (CD) direction respectively (Figures 3 & 4).

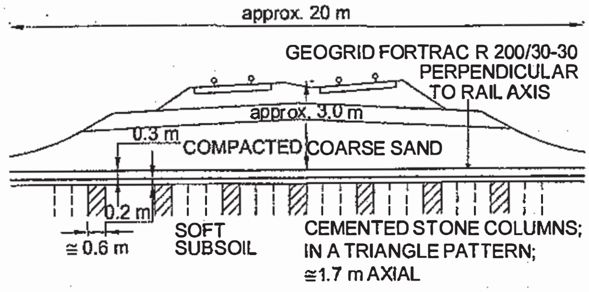

Figure 3. Project Southern Bypass Stendal, segment "PfA 4.3"

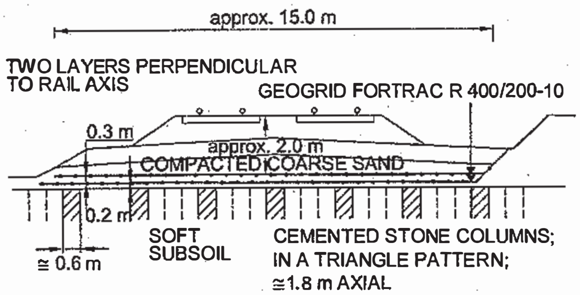

Figure 4. Project Southern Bypass Stendal, segment "PfA 4.6"

The main reason for such a high-strength double-layered reinforcement at PfA 4.6 was the small embankment height, resulting in an unfavorable stress-distribution i.e. in a low "pile efficiency" (Hewlett & Randolph 1988): a high portion of the stresses is not born directly by the columns, but have to be born first by the geogrids overbridging the columns. Further factors were the unfavorable subsoil parameters, generally the safety philosophy of DB, especially for ICE-trains, doubts about "punching" still available at that time (Vogel 1995) and, last but not least, the lack of really founded experience (design was performed in 1994-1995; the monitoring at Werder-Brandenburg had just started, see above).

Both sections have been instrumented with flexible horizontal inclinometers at the level of column tops and reinforcement, and geophones (acceleration gauges) for monitoring the static and dynamic behavior of the structure. After completion of the entire ICE-link Hanover-Berlin in Summer 1998, the performance of both systems was tested by train-passing under increasing loads and velocities up to 330 km/h.

Deformations, geogrid strains (derived from the horizontal inclinometers) and oscillation velocities were far below the allowed values. Last measurements after more than two years of ICE-traffic indicate very low deformations and geogrid strains (mostly < 1%). It seems (unfortunately) that the scatter of subsoil parameters mentioned above makes a precise back-analysis for PfA 4.3 and PfA 4.6 not realistic. Generally, the system resources seem to be remarkable in these cases. Both structures have been approved by FRA also.

5 PROJECT KÖRGRABEN (STATION RATHENOW)

In this case the high-speed ICE-link Hanover-Berlin crosses in the region of the Rathenow rail station a longer area of soft subsoil with a thickness varying from 0.5 m to about 6 m from the terrain downward (old flat river bed filled by young soft sediments). The ground water level ranges from 2 m to 3 m below surface. The firm soil layer in depth consists of gravelly sands.

At this segment of the link the rails had to be installed on an infinite concrete slab ("concrete slab track"), which is the most actual concept of DB for ICE-trains. All versions of this track system are more sensitive to settlements than the common ballast-bed system: thus, embankment and foundation deformations are rigorously restricted.

An additional problem was the low railroad level equal to the terrain, dictating together with the high ground water level the thickness of the bearing structure. Consequently, the system chosen comprises a relatively thin geogrid-reinforced soil body (not really embankment, but a block embedded in the ground) set on lime-cement stabilized soil columns as vertical bearing elements founded in the gravelly sands (Figure 5).

The columns are positioned in a semi-triangular pattern with about 1.6 m axial spacing and a diameter of approx. 0.6 m. The design analysis asked due to the extreme deformation restrictions for a geogrid providing a total strain of < 1.5% for hundred years design life. A specially produced uniaxial geogrid Fortrac® R 800/100-20 A with an UTS of 800 kN/m in longitudinal direction (MD) and an ultimate strain of only 3% was installed in two layers parallel and cross to the rail axis respectively (Figure 5). In this case no additional reinforcement for spreading forces was needed because the system is completely embedded in the surrounding soil.

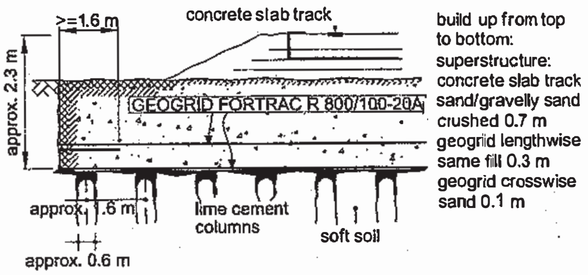

Figure 5. Project Körgraben (Rathenow station): cross-section

The structure was instrumented similar to the Southern Bypass Stendal Projects (see above). Immediately after completion in 1997 tests by a special very heavy oscillating equipment were performed, simulating ICE-train drives for many days, and varying frequencies and amplitudes due to the critical character of the structure (soft subsoil of varying depth, small thickness of reinforced earth block, high speeds and sensitive concrete slab track). Neither deformations, nor accelerations succeeded the allowable values. Additionally a temporary embankment was set on top of the system for 3 months simulating a train-equivalent surcharge. The maximum deflection of the geogrids between the columns was < 10 mm, and no deflections on the surface could be registered. In Summer 1998 the structure underwent additionally the same real train-drive procedures like the Southern Bypass Stendal. After that the materials and the system were finally approved by DB and FRA and put into operation.

6 PROJECT HARPER MÜHLENBACH

In 1998 DB arranged to extend the important west-east rail link between Uelzen and Stendal near the former boarder between West and East Germany. This railway line was first put into one-track-service in 1873 and was subsequently extended to two tracks between 1900 and 1906. In 1945, traffic was suspended in the occupation-zone border region.

The Section 51 at "Harper Mühlenbach" of about 0.5 km length is located on an embankment up to 6.5 meters high and 10 m wide at the crest. There had been no traffic or maintenance work there for more than 50 years. It comprised insufficiently compacted sand with silty components on soft foundation soil (decomposed peat). The ground water reaches often the embankment toe. Local and overall stability was insufficient, serviceability doubtful.

Therefore, the following work had to be done: first, widening of the crest of embankment from 10.0 m to 11.3 m to produce the required new standard profile for a two-track line, and second, increasing the stability of the embankment and its foundation taking into account a new train speed of 160 km/h.

For ecological reasons widening of the embankment base was not allowed. The solution found to be optimal is depicted in Figure 6, which is self-explaining. It comprises a partial new embankment on geogrids and cemented stone columns ("increasing global stability"), which has at the same time over-steep geogrid-reinforced "green" slopes ("widening the crest without widening the base").

For reinforcement on top of the columns high-strength uniaxial geogrids Fortrac® R 400/50-30 T (UTS 400 kN/m) and Fortrac® R 150/30-30 T (UTS 150 kN/m) cross and parallel to the embankment axis respectively were used (the cross-geogrids are stronger due to the spreading forces, see Chapter 2). Due to the existing old part of embankment beneath reinforcement level and pre-consolidation some upward counter-pressure on geogrids in the space between columns was (carefully) assumed, reducing the calculated tensile forces (see Chapter 2).

The slope reinforcement consists of different layers of lighter Fortrac®. According to EBGEO (1997) the dimensioning was based on Bishop's circle analysis and on block-sliding analyses.

Construction was completed in Summer 1999, test drives by heavy trains were performed in Autumn 1999, regular traffic started in December 1999.

Vertical and horizontal deformations and deflections are being measured. After three measurement sessions the registered values are negligible.

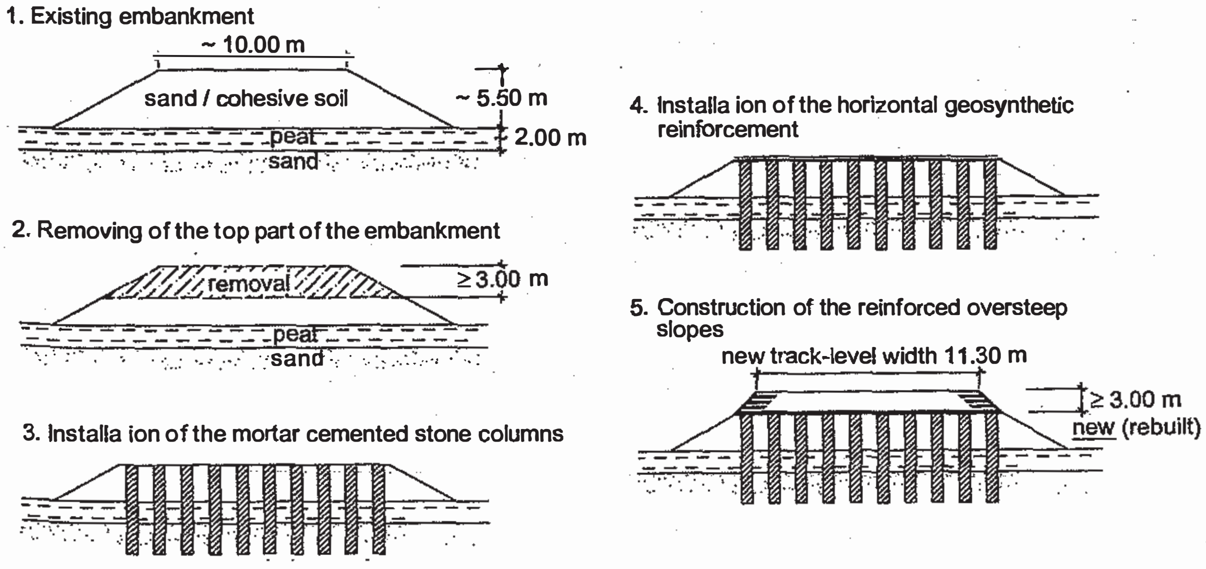

Figure 6. Project Harper Mühlenbach: concept, stages, components

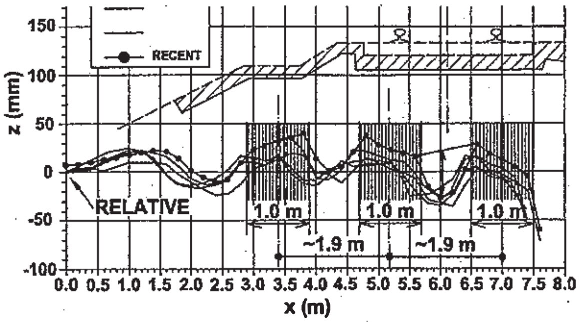

Figure 7. Werder-Brandenburg: recent deformations of 1st geogrid just on top of pile caps (note the cap contours).

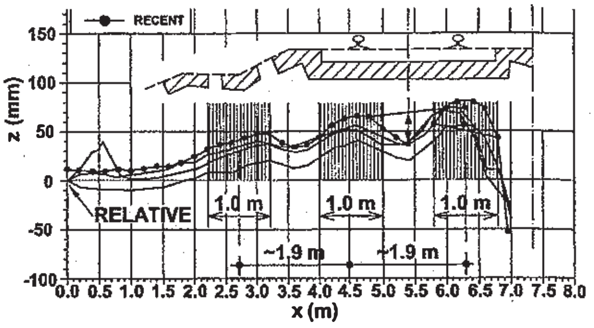

Figure 8. Werder-Brandenburg: recent deformations of 3rd geogrid 0.5 m above caps (note the smoothed contours).

It is the first DB-project combining a partial new "reinforced embankment on columns" and "geogrid reinforced slopes" to an integral structure. More details on design considerations, dimensioning procedures and construction techniques are reported in Alexiew et al. (2000).

The combined structure has been approved by DB and FRA.

7 WERDER-BRANDENBURG: MONITORING OF THE "OLDEST" PROJECT IN OPERATION

At the time of deciding to accept the geogrid-reinforced embankment on piles for this project in 1994, DB as yet had no experience of geogrid-reinforced embankment constructions on piles. DB and FRA called for verification of the concept and certification of stability and serviceability for a monitoring program. It includes two comprehensively instrumented scientific measurement cross-sections. The behavior of the structure has been systematically observed since 1994. A large quantity of vertical and horizontal inclinometers, deflectometers and resistive strain gauges on the geogrids have been installed. It is the most detailed, precise and long lasting measurement program worldwide for systems of the type discussed, being performed by the LGA-Geotechnical Institute in Nuremberg. Meantime measurements are running since about 6 years under traffic. The static geogrid strains are max ≅ 1.5% tending asymptotically to values < 2%, and their increase tends to zero, the max dynamic strains are < 0.02%. More detailed information including earlier stages, too, can be obtained e. g. from Alexiew & Gartung (1999). The long-term monitoring has confirmed the stability and serviceability of the structure Figures 7 & 8 (courtesy LGA) show typical results for the settlements in two different geogrid levels (see Figure 2 also), and, in fact, the actualshape of the geogrids and some tilting of the cap plates.

(Note: the horizontal and vertical scales are very different!). It should be pointed out that the deformations depicted do not reach the ballast bed.

REFERENCES

Alexiew, D. 1996. Modified Redistribution of Tensile Forces of Biaxial Span Reinforcement Between the Pile Caps. *HUESKER Synthetic, internal report (unpublished).*

Alexiew, D., Gartung, E. 1999. Geogrid Reinforced Railway Embankment on Piles - Monitoring 1994-1998. *Proceedings Geosinteticos '99. 1st South American Symposium on Geosynthetics*: 403-411.

Alexiew, D., Pohlmann, H., Lieberenz, K. 2000. Railroad Embankment with Reinforced Slopes and Base on Stone Columns. *Proc. 2nd European Conference on Geosynthetics EuroGeo2000, October 2000*: 239-244. Bologna: Patron Editore.

Brandl, H. 1994. ABS Berlin to Magdeburg (km 37.060 to km 59.419) Werder to Brandenburg section. *Geotechnical report on soil characteristics (in German, unpublished).*

British Standards Institution BS 8006:1995. 1995. Code of Practice for Strengthened/Reinforced Soils and Other Fills. London: BSI.

EBGEO Emfehlungen für Bewehrungen aus Geokunststoffen. 1997. (Recommendations for Reinforcement with Geosynthetics, in German). German Soc. Soil Mech. Geot. Eng. (ed.) Berlin: Ernst & Sohn.

Hewlett, W.J., Randolph, M.F. 1988. Analysis of Piled Embankments. *Ground Engineering, Vol.21, No.3*: 12-18.

Kempfert, H.-G., Stadel, M., Zaeske, D. 1997. Berechnung von geokunststoffbewehrten Tragschichten über Pfahlelementen. *Bautechnik, Vol. 74, Heft 12*: 818-825.

Kempfert, H.-G., Zaeske, D., Alexiew, D. 1999. Interactions in Reinforced Bearing Layers over Partially Supported Underground. *Proceedings of the 12th European Conference on Soil Mechanics and Geotechnical Engineering*: 1527-1532. Rotterdam: Balkema.

Vogel, W. 1995. Application of a New Construction Method for the Substructures of Railroads. Analysis Report. *Deutsche Bahn AG (German Railroads) (in German, unpublished).*