

Geogrid Reinforced Railway Embankment on Piles - Performance Monitoring 1994 - 1998

D. Alexiew, Dr.-Ing.

HUESKER Synthetic GmbH & Co., Gescher, Germany

E. Gartung, Dr.-Ing.

LGA Geotechnical Institute, Nuremberg, Germany

ABSTRACT: In 1994 a stretch of about 2 km total length of the German Railways -link Berlin-Magdeburg in areas with soft subsoil was rebuilt as geogrid-reinforced, relatively flat embankment on slender piles. It was the first application of such a system in a railroad in Germany. Due to the lack of experience in dimensioning and construction a monitoring programme has been performed from spring 1994 until autumn 1998. Subsoil conditions, system geometry and materials, dimensioning concepts and instrumentation are described. Important results of the system's behaviour during four years under traffic (160 km/h) are reported and analysed. It is probably the most detailed and long lasting monitoring programme for such structures. Based on the results the stretch was certified for unlimited traffic by the German supervising authorities.

KEYWORDS: Geogrids, embankment, piles, railroads, long-term monitoring.

1 INTRODUCTION

During the years 1994 to 1995, the approximately one-hundred-year-old railway line between Berlin and Magdeburg was upgraded to withstand a speed of 160 km/h and a greater load. Organogenic soils were found on the stretch between Werder and Brandenburg. To provide for the foundation of the railway embankment, a conventional soil replacement was made in the thinner highly compressible soil layer. In sections in which the soft soil layers extended to a greater depth, a geogrid reinforced embankment on piles was installed as specially proposed by an international consortium of tenderers.

At the time of deciding to accept the proposal, which had advantages in terms of construction cost, construction time and environmental protection, Deutsche Bahn (German Railways) as yet had no experience of geogrid reinforced embankment constructions on piles as permanent foundation. Since this method of construction was also not covered by railway rules and regulations, the terms of construction had to be drawn up specifically for this case. The client and the construction supervisory au-

thorities called for certification to the effect that the new type of foundation was sufficiently safe and fit for use, this to be based among other items on a monitoring programme. The monitoring programme includes two comprehensively outfitted scientific measurement cross-sections MQS I and MQS II, in which the behaviour of the geogrid reinforced embankment has been systematically observed since 1994 and 1995 respectively. The equipment of the first measurement cross-section, MQS I, and first measurement results were presented in Verspohl & Gartung (1995) and Gartung E. et al. (1996).

2 SUBSOIL

In the region of the railway line, the sequence of subsoil layers comprises organic soil having a depth of from 2 to more than 20 m under a sandy stratum. Below lies loosely deposited, uniformly sand containing organic admixtures, which transfers to densely deposited sand or boulder clay as depth increases and can then serve as good load-bearing foundation soil capable of taking vertical pile loads. The ground

water extends from close to ground surface to a maximum depth of 2 m. The organic soils have a very low permeability.

They partially comprise highly fibrous peat which, in normally consolidated state beside the rail route, has a natural water content of 300 to 600% which is above the liquid limit. The modulus in the oedometer-test varies here between $E_s = 0.2 \text{ MN/m}^2$ and 0.8 MN/m^2 . At $E_s = 2$ to 6 MN/m^2 on account of pre-consolidation, conditions were distinctly better underneath the bottom of the old railway embankment. At $c_u > 15 \text{ kN/m}^2$, the undrained shear strength under the embankment was also higher than beside it, where measured values reached 10 kN/m^2 and sometimes less (Brandl 1994).

Apart from peat, the foundation soil contains sandy to clayey silt having a high content of organic components. Depending on construction, these soils are characterised locally as mud or bog lime. At 30 to 225 %, their water content in normally consolidated state is above the liquid limit, so they may be regarded as mushy to liquid in consistency. Water content was lower under the old railway embankment as a result of consolidation, so the condition was judged to be mushy to soft. Because the organic components are unevenly distributed, the density and the undrained shear strength of the organic silts each vary within a relatively wide range. Values of $c_u = 10$ to 50 kN/m^2 were determined for the mud and bog lime beside the embankment, values of 20 to 100 kN/m^2 underneath it. The modulus was also observed to have a correspondingly broad range of variation.

By way of example the soil profiles of the two measurement cross-sections MQS I at km 45.4 and MQS II at km 44.8 are described shortly. In MQS I, the soft soil layer comprising peat and bog lime extends to a depth of up to 5.0 m below ground surface, with underneath a 3.0 m thick silty layer of fine sand. Good load-bearing boulder clay is reached at about 8.0 m under ground surface. In contrast, the MQS II soil profile, under a 1.2 m sandy filling, comprises a bog lime of mushy to soft consistency extending to a depth of 6.4 m under ground surface, fol-

lowed by loosely deposited, poorly graded fine to medium sand having organic contents. Even in greater depths the sand is not densely deposited and not classifiable as load-bearing subsoil.

Speaking clearly, the subsoil conditions in MQS II are remarkably poorer than in MQS I.

3 EMBANKMENT CONSTRUCTION ON PILES

The foundation soil was investigated in two phases for planning purposes. Immediately before construction work began, the thickness of the soft soil layer was examined again using closely spaced dynamic penetration testing, to estimate the final expected length of piles, and to avoid piling on some stretches with very thin soft layers. Slender "ductile cast-iron" driven piles with precast RC-caps on top were used in a square pattern, with total lengths varying from 10 m to 30 m, while soft subsoil thickness varied from 4 m to 20 m.

The geogrid reinforced embankment construction on piles was installed at 8 sections of the line, amounting to a total length of about 2 km. Both tracks were treated separately, one track at a time having to be kept available for rail traffic. The respective working track was secured by a temporary sheet pile wall at the middle of the railway embankment.

Fig. 1 illustrates the load-bearing elements of the structure. 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 due to the strict long-term deformation limitations, having an ultimate tensile strength (UTS) of 150 kN/m in both directions and a corresponding strain of about 13%. For the bottom and middle layer 10 m wide panels were prefabricated in-plant by special technique. The vertical loads of the piles are transferred to the densely deposited sand at greater depth. The organic, mushy to soft soil layer has sufficient resistance to support the slender piles

Figure 1. Geogrid reinforced embankment on piles

against buckling. Between the pile caps, this layer could also directly bear a small portion of the vertical forces imposed by the embankment, so the whole load does not have to be borne by the membrane-type bearing effect of the geogrid reinforcement and the arching effect of the embankment.

Five years ago (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. Additionally for this project 3 % *total* (say short-term plus creep) strain of geo-grid were allowed for 120 years design life. No difference was made between (short) construction stage, start of traffic and (long-term) operation stage. It was a conservative requirement.

Accordingly, comparison calculations based on several computational models were carried out at the design stage. Investigations began with a quasi-elastic plate bearing calculation using the finite-element method and very sim-

plified beam models. Calculations were made as well with the formulation described later by Kempfert et al. (1997), which also took into account the bearing effect of the soft soil between the pile caps. This effect was varied in the calculation so as to obtain a general view of its influence. More detailed explanations can be found in Alexiew et al. (1995). Finally, BS 8006 (1993) (being a draft at this time) was used too in dimensioning the reinforcement. The final solution as described above was believed to be conservative to some extent. Because the entire system was remarkably less expensive than any other solution, taking into account all financial, technical and ecological aspects, a conservative approach was acceptable. However, since no sufficient body of experience was to hand on this new type of construction for a railway foundation, it was considered appropriate, for the purpose of assessing safety and serviceability to set up a long-term monitoring programme.

The project was monitored from the outset of the construction work. The first construction phase on the southern line from Magdeburg to Berlin was completed as trial stretch in May 1994 and provided with the scientific measurement cross-section MQS I. By doing this, quantitative observations on the load bearing performance of the geogrid reinforced, low-level embankment cross-section on piles became available at a very early stage, so the basic suitability of the new construction method could be confirmed by the first measurement results.

In the summer of 1995, the second scientific measurement cross-section, MQS II, was set up on the northern track from Berlin to Magdeburg. A stretch of line was chosen in which the detailed investigation had found particularly unfavourable subsoil conditions (see chapter 2 above). Consequently, settlement and deformation of the system are different in the two measurement cross-sections, as a result of the differences in the subsoil layers and the depth to which the piles are driven (see chapter 5).

The scientific measurement cross-sections are equipped with extensometers, wire strain gauges and recording accelerometers (Fig. 2). The vertical bar-type extensometers, which can only be read off between trains, are used to measure settlement and differences in settlement within the embankment. Settlement can be determined separately for the pile caps and for the spans between them. Horizontal extensometers were arranged in place to detect possible spreading. The wire resistance strain gauges measure the strains of the geogrids and the piles both under static load and under train traffic. Finally, accelerometers on the pile caps are used to determine vibrations under trains.

Figure 2. Equipment provided in the scientific measurement cross-sections

To provide for long-term observation of all rail sections equipped with the geogrid reinforced embankment construction on piles, a further eight, simpler observation cross-sections were set up in addition to the two scientific measurement cross-sections and have been measured at regular intervals. These sections are equipped at three levels with horizontally arranged, flexible plastic tubes. The deflection of the buried tubes, which corresponds to the deformation of the embankment, is measured by introducing a measuring head. A comparison of the deformation curves provides information on changes in the geometry of the embankment over time. By comparing the measurement results obtained in the "simpler" measurement cross-sections with the observations made in the scientific measurement cross-sections, the data obtained at the more simply equipped observations points can itself be more comprehensively interpreted, too.

In the "simpler" measurement cross-sections, surface settlement and spreading deformations are determined by geodetical measurements.

The monitoring at a total of ten sections (2 x "scientific" & 8 x "simpler"), is complemented by observation of the ground water table and by measurement runs with a "measuring train".

5 MEASUREMENT RESULTS

5.1 Vertical Deformation

The vertical extensometers provide information on the settlement at measurement points at different depths, making it possible to determine the vertical deformation of the reinforced soil zone and its change in thickness. Taking MQS I as example, Fig. 3 shows the measured vertical displacement in the plane of the bottom geogrid

layer in a vertical section through the piles. It can be seen that deformation under the track is distinctly greater than outside of the track region. Where the pile caps are equipped with two recorders, tilting of the pile cap is recognisable from the difference in vertical displacement. The settlement of the piles and sagging of the reinforced soil can be read off the graph in absolute terms. Note: The straight-line connection of values measured at discrete points does not of course correspond to the actual shape of the geogrid, which would probably about follow a catenarian curve.

Figure 3. Vertical displacement in the plane of the bottom geogrid layer in section through the piles in MQS I

The settlement of the pile caps in MQS I is in the order of 7.5 to 15 mm. Amounts of up to 55 mm were measured for vertical displacement of the bottom geogrid layer between the piles under the track in MQS I. The maximum settlement in the plane of the bottom geogrid layer between the piles outside of the track region is about 35 mm. The difference between settlement above and between the pile caps indicates a sag of at most 40 mm in the bottom geogrid between the piles directly under the track. The reinforced soil (coarse sand) zone has compressed by between 16 and 30 mm in the course of the observation period under traffic (not shown). This could be an indication of insufficient compaction during construction. The generally no more than slight tilting of the pile caps has changed somewhat by comparison with

condition as installed, but the measurement results do not reveal any systematic trend.

From the course of the vertical displacement over time in MQS I (Fig. 4), it can be seen that pile settlement begins slowly and has largely abated after about two and a half years. The increase in settlement in the plane of the bottom geogrid layer between the piles was relatively large during the first few months under traffic load. However, the rate of settlement steadily reduced after that and following four years of observation, has become so slight that by semi-logarithmic extrapolation from the measurements, the long-term prognosis can be given that no further noticeable vertical displacement would be anticipated in measurement cross-section MQS I (Fig. 5).

Figure 4. Course of vertical displacement over time in the plane of the bottom geogrid layer, section through the piles, MQS I (see Fig. 2)

limit values considered admissible when planning the construction.

Figure 5. Semilogarithmic representation of the vertical displacement in Fig. 4

Measurement "scientific" cross-section MQS II was set up about a year later than MQS I. Accordingly, the observation period in this case, from 1995 to 1998, amounts to just three years. Nonetheless, greater vertical displacements have so far been measured in MQS II than in MQS I, which would be attributable to the influence of the very poor subsoil conditions (see chapter 2).

Amounts of between 35 and 85 mm have been determined for the deflection in the reinforced soil zone in association with the maximum driven-ductile-pile settlement of up to 55 mm and an overall settlement of up to 121 mm in the plane of the bottom geogrid layer (Fig. 6). As opposed to MQS I, no noticeable reduction in the thickness of the reinforced soil was detected over time under traffic load in MQS II. If it is to be assumed that the final compression of the reinforced soil depends primarily on the quality of the construction work, then it can be concluded that precision in laying the reinforcement and compacting the soil material (especially near the sheet pile wall at the middle of the railway embankment) was greater in the region of MQS II than in MQS I, which was built at the beginning of the project.

Unlike MQS I, where pile settlement developed over a prolonged period of time, the course of vertical displacement over time in MQS II indicates a fast abatement in settlement of the piles (Fig. 6). The relatively large degree of pile settlement had been occurred before the commencement of regular operations. Between the piles, settlement was still increasing very slightly even three years after the beginning of traffic. However, an analysis of the settlement rate shows that based on the data available to date, long-term settlement within an allowed order of magnitude can also be prognosticated for MQS II (Fig. 7). While the settlement is indeed greater than in MQS I, it comes below the

Figure 6. Course of vertical displacement over time in the plane of the bottom geogrid layer, section through the piles, MQS II (see Fig. 2)

5.2 Horizontal Deformation

In both measurement cross-sections, the changes in horizontal distances taken across the longitudinal axis of the embankment vary within the range of a few millimetres. Only at the centre of the embankment, apparently when pulling the sheet piles, some local loosening has occurred, and with it a horizontal displacement at the extensometer measurement points. The influence of the deflection of the extensometer bars on account of vertical deformation of the embankment has to be taken into account when evaluating the horizontal extensometer measurements. Having corrected for deflection, the measured values indicate a horizontal expansion in the order of 0,2 % to 0,3 % within the half-embankment cross-section under the region of the track.

Figure 7. Semilogarithmic representation of the vertical displacement in Fig. 6

In the course of the geodetic survey of the 8 "simpler" measurement cross-sections, spread of 40 to 50 mm was observed over the full width of 15 m of the embankment in two out of ten cases, spread of 10 to 20 mm in another two cases and of 0 to 10 mm in the remaining six cases. These figures are insignificant in terms of the railway embankment's serviceability. Greater spreading deformation would be anticipated in regard to higher embankments and a comparatively poorly bearing subsoil.

5.3 Strains of the Geogrid

The strains of the geogrid were measured by resistance strain gauges (DMS) in the top and in the bottom geogrid layer, both "statically" between trains and "dynamically" under trains in transit. The course of the "static" strain over time has developed similarly to the vertical displacement shown by way of example in Figs. 4 and 6. In terms of order of magnitude, consistency has also been good between calculated strain determined from the deformation line of the embankment body as indicated by the extensometer measurements, and strain under static load as measured by the strain gauges (DMS). No strains of more than 1,7 % are registered until now by the DMS, indicating some overdimensioning of the geogrids. No systematic difference has been observed between strain in

the top and in the bottom geogrid layers, which indicates a membrane-type-behaviour of the triple-reinforced layer.

The system is dynamically loaded under trains in transit. The DMS have measured the strain of the geogrids under numerous different types of train in transit. Fig. 8 gives an example of strains in the geogrid while being passed over by a goods train. The reaction to each individual wheelset can clearly be seen, as also, distinctly, the greater load of the locomotive. While different dynamic strains have been measured according to the loads and characteristics of different train types (passenger trains, goods trains, express trains, etc.), the strains have not been found to depend on speed up to 160 km/h for the geogrids used.

Perpendicular to the embankment, the "static" preliminary strain of the geogrid simply increases while a train is in transit (Fig. 8 a), as against which, a partial alleviation of load occurs often before the increase in strain under every train passage as measured by the gauges in longitudinal direction (Fig. 8 b). It could be caused by the "bow wave" that precedes the train. The alleviating difference in strain amounts to about 60 $\mu\text{m}/\text{m}$ in MQS I and about 120 $\mu\text{m}/\text{m}$ in the "very poor subsoil" MQS II.

The additional strain attributable to traffic load amounts to at most about 120 $\mu\text{m}/\text{m}$ (0,012 %) in MQS I and up to 250 $\mu\text{m}/\text{m}$ (0,025 %) in MQS II. Like settlement, static strain has all the time increased (at a distinctly decreasing rate). On the contrary, in the course of the measurements made over four years, there has been practically no change in the order of magnitude of the "dynamic" strains of the high-strength geogrids used.

Figure 8. Typical additional "dynamic" strains of geogrid under train passage

Evidently, the properties of the soft subsoil are not just important with regard to the "external" behaviour of the overall load-bearing system, they also influence the strain imposed on the internal load-bearing members, as is to be seen also from the registered difference between the "dynamic" strains of the geogrids in the two measurement cross-sections having different soil conditions.

The "dynamic" strain attributable to traffic load is (for the reinforcement used) very slight by comparison with the "static" strains caused by the dead weight of the construction. It would appear that some of the deformation from the load imposed by the first passages of trains is "memorised" as "quasi-static" strain. The geogrid-reinforced system is "prestressed" to a degree in the process, as a result of which deformation under subsequent traffic loads is no more than slight. A more precise analysis of this phenomenon still remains to be completed.

6 SUMMARISING EVALUATION OF THE MEASUREMENT RESULTS

The measurements conducted over a period of four years under train traffic have revealed that the load-bearing system comprising a high-strength geogrid reinforced embankment on piles is capable of satisfying requirements. The properties of the poorly load-bearing soil influence the deformation imposed on all bearing elements. The more unfavourable the soil conditions, the greater is the settlement of the overall system and also the stress and forces in the soil reinforced with high-strength geogrids. Deformation of the reinforced embankment has increased with time, but the rate of deformation has fallen steadily off, so that the system has

nearly reached a final state of equilibrium in the course of just a few years.

It is recognisable from the strain measurements in the geogrids that the reinforcement is subject to high stress and is therefore decisive in terms of the safety and serviceability of the load-bearing system. No difference has been observed between the tensile forces of the three reinforcement layers (top, middle and bottom). It can be concluded, that a membrane-bearing mechanism takes effect even in the three-level-reinforced system contrary to the plate-bearing and similar mechanisms which were alternatively assumed some years ago (see chapter 3).

The stress imposed on the geogrid is distinctly greater under the track than outside of the track region. From the associated variability of the tensile forces in the reinforcement, it can be concluded that the interaction forces between geosynthetic reinforcement and soil and the compatibility of deformations are an important factor.

The measurements would lead to the conclusion that the system described has been sufficiently well dimensioned (to some extent on the safe side), including the geogrid-reinforcement. The "German" dimensioning concept described later with some modifications by Kempfert et al. (1997) seems reliable. The dynamic effects and the cumulation of remaining deformation from the first traffic loads would need to be analysed in more detail.

The strains measured (and prognosticated by extrapolation) in the geogrids remain below the allowed level of 3 % established (conservatively) at the design stage. The stability of the rail road foundation is well guaranteed over time. The system is perfectly fit for use with little requirement for maintenance. The deformation recorded to date has not given rise to problems with the rail road. Personnel operating over the line in question have confirmed that trains run better on the sections comprising geogrid reinforced embankment on piles than on those which underwent a conventional soil replacement.

On the basis of the experience, observations and measurements the stretch with geo-grid-reinforcement on piles was officially certified

for unlimited time by German supervising authorities in autumn 1998.

In the meantime further high-strength geogrid-reinforced systems on piles are under traffic inclusive the German bullet trains (ICE) (Alexiew D. et al. 1999).

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