Pile-supported embankments on soft ground for a high speed railway - Load Transfer, Distribution and Concentration by different construction methods

M. Raithel & A. Kirchner
Kempfert + Partner Geotechnik, Wuerzburg, Germany

H.-G. Kempfert
University of Kassel, Germany

ABSTRACT: For the foundation of traffic infrastructure in areas with soft subsoil often embankments supported by piles are necessary due to the settlement requirements. For sufficient load transfer into the piles different construction methods are possible. For the construction of a high speed railway line in China reinforced concrete slabs, a cement stabilization of the embankment material and geogrid reinforcement on top of the piles were used. The different methods are described and important field monitoring results are presented.

1 INTRODUCTION

In areas with soft subsoil embankments have often to be founded on piles or columns, especially if restricted settlement requirement exists. Thereby a sufficient load transfer into the piles is necessary.

Without any constructive elements for load transfer and distribution an arching effect in the embankment will be present, due to the higher stiffness of the piles compared to the soft soil. The mechanism of stress redistribution can be modelled by a system consisting of several arching shells. In many cases this is not sufficient for settlement reduction, especially if there is a risk of high cyclic/dynamic loading.

For a high speed railway line in China therefore three different construction methods for a better and safe load transfer, distribution and concentration were carried out:

- Reinforced concrete slab on top of the piles
- Horizontal geogrid reinforcement on top of the piles (so-called “geosynthetic-reinforced pile-supported embankment”)
- Cement stabilization of the embankment material

In this contribution the design and construction of the pile-supported embankments will be presented.

2 PROJECT

Between Beijing and Tianjin 115 kilometres of high speed railway are being built by order of the Chinese Railway Department. The railway line will go into service at the Olympic Games 2008. With a design speed of 350 km/h, the superstructure of the line will be constructed with the so-called slab track system “System Bögl” developed by Max Bögl GmbH & Co. KG - Germany. The Bögl slab track system consists of laterally tensioned, prefabricated slabs with mounted rail fastenings.

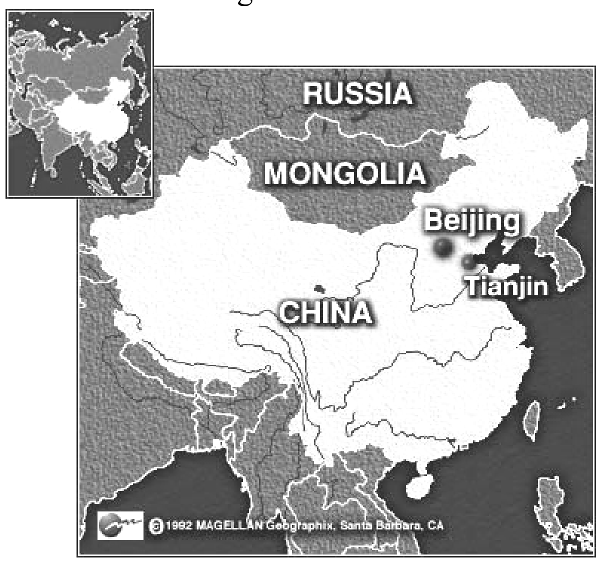

Figure 1. High speed railway between Beijing and Tianjin.

About 80% of the railway line will run on a structure consisting of single-span and multi-span bridges with standard span lengths of 24 and 33 m and in some cases between 60 and 120 m. The remaining length of the track will run on an embankment with piled foundations.

Due to subsoil conditions characterized normally by soft to stiff silt and clay down to depths of 50 – 80 m and a groundwater level just beneath the ground surface, all structures were founded on piles with lengths up to 70 m.

Considering the speed, the requirements concerning settlements of the foundation with 15 mm after construction of the slab track are very high. In order to determine the actual bearing capacity of the pile foundations pile load tests were conducted on special test piles (see Raithel et al. 2006). To guarantee the necessary quality, working piles (auger- and driven piles) were also tested.

3 PILESYSTEM – AUGER- AND DRIVEN PILES

For the foundation of the embankments two different pile systems are used.

The CFA-piles are drilled with continuous flight augers up to depth of 28 m. The diameter of the auger is about 40 cm and the diameter of the hollow stem is about 10 cm.

Additional precast concrete driven piles (prestressed) with diameter 45 cm and a total length up to 35 m were used. According to our experiences this system provides very good bearing capacities if the piles are properly produced and installed. The coupling was achieved by welded joints.

Figure 2. Continuous flight augers and centrifugally precast concrete driven piles.

In order to determine the actual bearing capacity of the pile foundation, pile load tests on driven piles as well as on auger piles with lengths of 25 – 35 m each were conducted (Raithel et al. 2006).

A problem is the group effect of the pile foundation, due to the small separation of the piles (distance of 1.2 to 2 m). Therefore the settlements of the pile group are increased compared to the result of single-pile tests. The group effect of the piles was analyzed by singe pile tests and special calculation programs for definition of the group effect. Further information can be found in Raithel et al. (2006).

4 STANDARD CONSTRUCTION - REINFORCED CONCRETE SLAB

Normally a reinforced concrete slab with a thickness of about 50 cm on top of the piles for a safe load transfer, distribution and concentration was used. On both sides a cantilever retaining wall was constructed. A schematic view of the pile supported embankment is shown in Figure 3 and a picture is given in Figure 4.

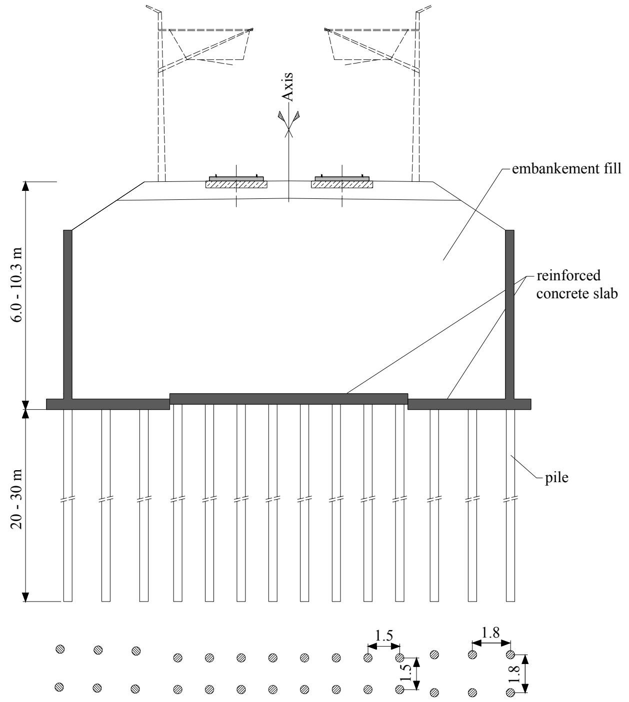

Figure 3. Pile supported embankment with concrete slab on top of the piles.

Figure 4. Construction of retaining walls.

5 HORIZONTAL GEOGRID REINFORCEMENT ON TOP OF THE PILES

5.1 *General*

In recent years a new kind of foundation, the so-called "geosynthetic-reinforced and pile-supported embankment" (GPE) was established. Above the pile heads, the reinforcement of one or more layers of geosynthetics (mostly geogrids) is placed, see Kempfert & Raithel (2005). The application of such solutions is recently developed in Germany, see Alexiew & Vogel (2001). In the following the main principles of calculation and design and afterwards the construction in Beijing are shown.

5.2 *Calculation and Design*

The stress relief from the soft soil results from an arching effect in the reinforced embankment over the pile heads and a membrane effect of the geosynthetic reinforcement, see Figure 5 (Kempfert et al. 2004).

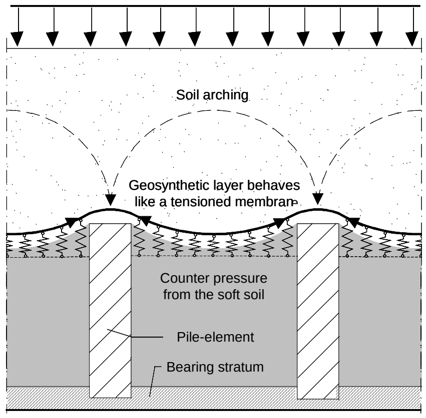

Figure 5. Mechanisms of load transfer and interaction.

Due to the higher stiffness of the columns 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 column heads and the surrounding soft soil.

The 3D-arches span the soft soil and the applied load is transferred onto the piles and down to the bearing stratum.

The stress distribution can be modelled in various ways. Figure 6 shows, for example, a system consisting of several arching shells (Zeaske 2001, Zaeske & Kempfert 2002).

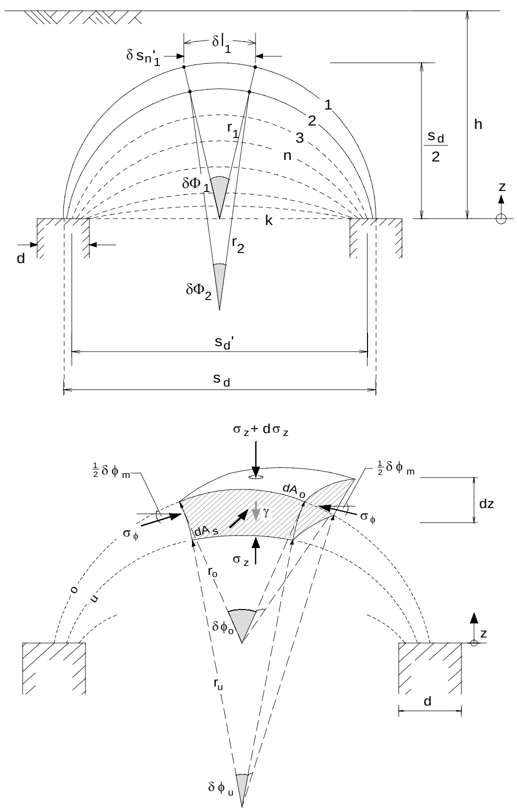

Figure 6. Theoretical arching model.

This model leads to a differential equation, which is a function of the described vertical stresses σ_z [z] in the arching system (Zaeske 2001):

$$-\sigma_z \cdot dA_u + \left(\sigma_z + d\sigma_z\right)\cdot dA_o - 4\cdot\sigma_\Phi\cdot dA_s \cdot \sin\left(\frac{\delta\Phi_m}{2}\right) + \gamma\cdot dV = 0 \tag{1}$$

For the areas above the arches a load depending stress distribution is assumed. The effective stress on the soft soil stratum σ_{zo} results from the limiting value consideration $z \rightarrow 0$ with t = height of the load depending arch, so the following equation can be formulated. Simplified σ_{zo} can also be derived from dimensionless diagrams (DGGT, 2003).

$$\sigma_{zo} = \lambda_1^{\chi}\cdot\left(\gamma+\frac{p}{h}\right)\cdot \left(h\cdot\left(\lambda_1+t^2\cdot\lambda_2\right)^{-\chi} + t\cdot\left(\left(\lambda_1+\frac{t^2\cdot\lambda_2}{4}\right)^{-\chi} - \left(\lambda_1+t^2\cdot\lambda_2\right)^{-\chi}\right)\right) \tag{2}$$

with:

$$\chi = \frac{d\cdot(K_{krit}-1)}{\lambda_2\cdot s_d}, \qquad \lambda_2 = \frac{s_d{}^2+2\cdot d\cdot s_d - d^2}{2\cdot s_d{}^2}$$

$$\lambda_1 = \frac{1}{8}\cdot(s_d-d)^2, \qquad K_{krit} = \tan^2\left[45° + \frac{\varphi'}{2}\right]$$

The loading of the reinforcement is expressed by the differential equation of the elastic supported cable, in which the vertical displacement z_W over the soft soil and the horizontal force H, (Zaeske & Kempfert 2002) are the unknown variables, see Figure 7.

$$\frac{d^2z}{dx^2} = \frac{q_{z,w}}{H} + \frac{k_{s,w}\cdot z_w}{H} \tag{3}$$

with:

$$H = \frac{2\cdot\int_0^i\sqrt{1+z_W{}'^2}\,dx + 2\cdot\int_i^j\sqrt{1+z_P{}'^2}\,dx - l_0}{2\cdot\int_0^i\left(1+z_W{}'^2\right)dx + 2\cdot\int_i^j\left(1+z_P{}'^2\right)dx}\cdot J$$

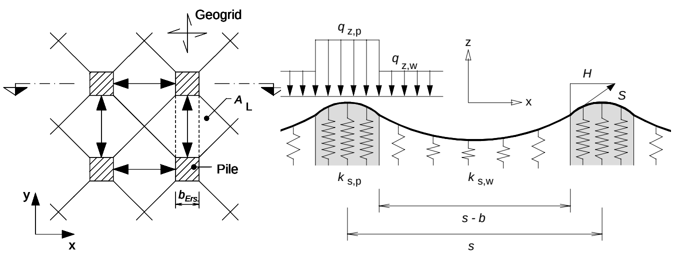

Figure 7. Loading of the reinforcement.

Finally the loading of the reinforcement S can be calculated directly as a function of the elongation ε (J = stiffness) of the geosynthetic (for dimensionless diagrams see DGGT 2003):

$$S[x] = \varepsilon\,[x]\cdot J = H\cdot\sqrt{1+z'^2\,[x]} \tag{4}$$

5.3 *Soil arching under cyclic loading*

Whereas the system behaviour (soil arching and membrane effect in geosynthetic reinforcement) under static loading is well-known, the bearing behaviour and the settlements expected under cyclic loading are not yet fully understood. Under cyclic loading the arching effect can only be formed in a very limited extent and part of the load carried directly by the piles can decrease remarkably, which results in an increase of the load on the soft soil and on the reinforcement. Due to the reduction of the soil arching, the strains in the geogrid and the surface settlements increase considerably. Based on the results of model tests and numerical investigations, the main parameters which cause a reduction of the arching effect have been identified (Heitz 2006). Critical geometrical and loading limits were worked out, see Table 1. For system values beyond these limits a modified calculation procedure is proposed which takes a soil arching reduction and an increase of the geosynthetic strains into account (Heitz 2006).

Table 1. Simplified requirements for consideration of cyclic effects on arching.

Cyclic loading	Geometry[1)]	reduction of arching
Large (railway - about 30 kPa)	> 1.5	negligible
	≤ 1.5	partly up to complete
Middle (roads - about 15 kPa)	> 0.7	negligible
	≤ 0.7	partly

[1)] see Figure 15

5.4 *Construction*

For the construction of the railway line from Beijing to Tianjin a geosynthetic-reinforced and pile-supported embankment" (GPE) was built in the city area of Beijing. Figure 8 shows a picture of the embedded geogrid. A schematic view of the pile supported embankment with the geogrid reinforcement is shown in Figure 9.

Figure 8. Embedded geogrid.

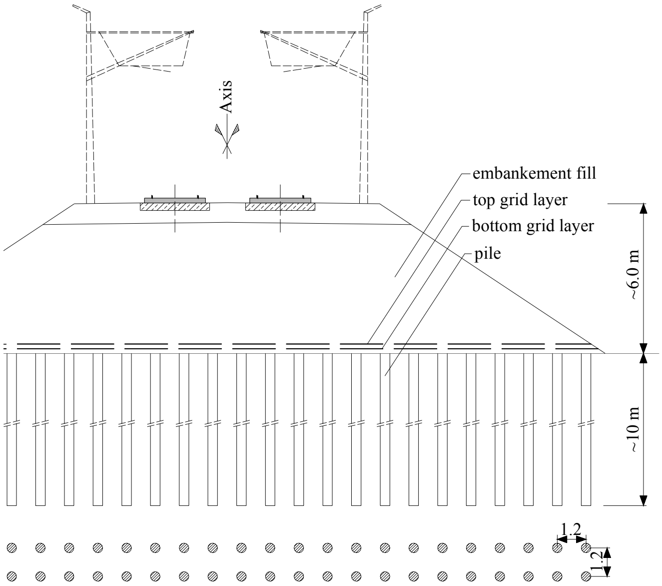

Figure 9. Geosynthetic-reinforced and pile-supported embankment Beijing.

6 CEMENT STABILIZATION OF THE EMBANKMENT MATERIAL

6.1 *Calculation and Design*

In sections with very low embankments a cement stabilization of the embankment material instead of the geosynthetic reinforcement is more reasonable, due to the reduction of the arching effect and the increase of the forces in the geogrid reinforcement by a high cyclic loading.

The cement stabilized embankment acts similar to a slab over the pile heads, whereas the expensive reinforcement can be saved. For the design of the cement stabilized embankment a Finite Element Model FEM was used, considering a so called unit cell, which means the consideration of one pile with the surrounding soil (infinite pile grid) in an axially symmetric model.

Figure 10 shows the situation before filling. A schematic view of the pile supported embankment with the cement stabilization is shown in Figure 11.

Figure 10. Situation before filling.

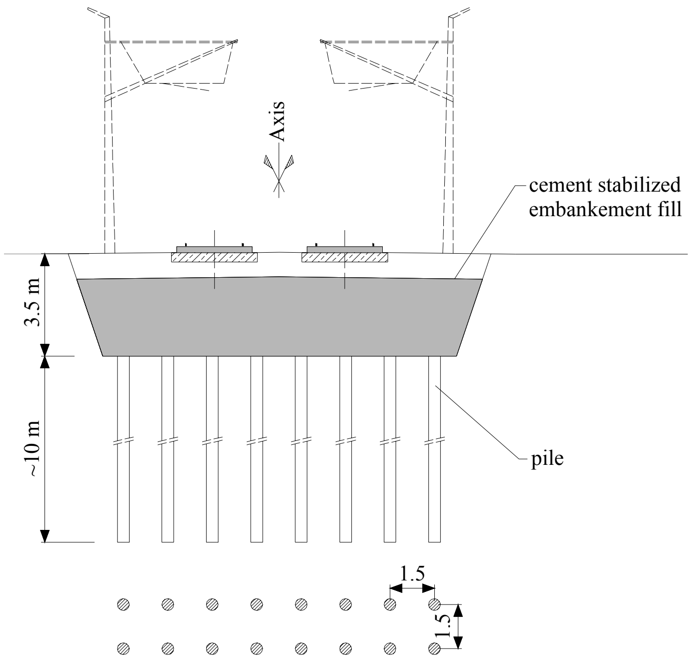

Figure 11. Cement stabilization in Beijing.

7 MONITORING

7.1 *Monitoring concept and Measurement cross sections*

Due to the settlement requirements a monitoring program for verification of the design and certification of stability and serviceability was installed. The different monitored cross sections have distances between 5 and 50 m. A large quantity of vertical and horizontal inclinometers and geophones were installed. Additionally, the settlements of the rails were measured.

In a typical measurement cross sections one horizontal inclinometer and up to four settlement plates are used for the examination of the deformation behaviour, see Figure 12.

In Figure 12 additionally the temporary overload for minimization of the settlements after the construction time can be seen.

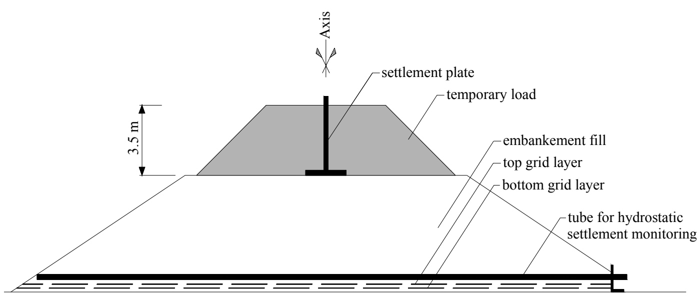

Figure 12. Typical measurement cross sections.

7.2 *Measurement results*

In January 2008, measurements had been performed for about 10 to 14 months. The long-term monitoring has confirmed the stability and serviceability. In December 2007 the slab track was installed in all parts of the railway line.

Figure 13 shows typical results for the settlements at different heights in a cross section with a reinforced concrete slab and Figure 14 the settlements of a section with a horizontal geogrid reinforcement on top of the piles instead of the concrete slab. In these sections the embankment is ultimately about 8.5 and 5.0 m high (following removal of the 3.5 m temporary load), respectively.

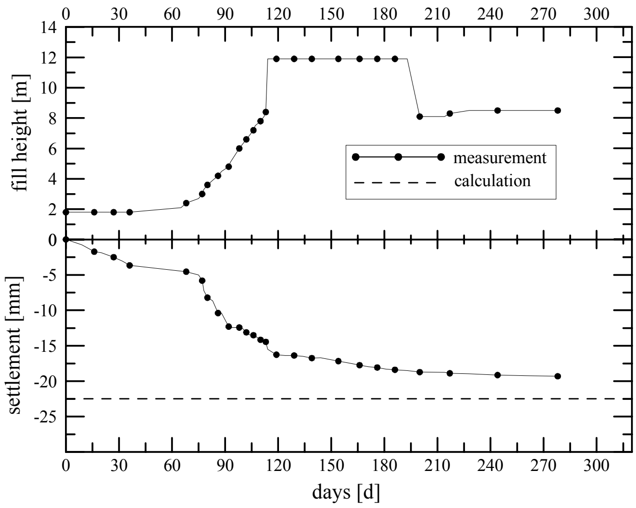

Figure 13. Settlements in a section with a concrete slab on top of the piles.

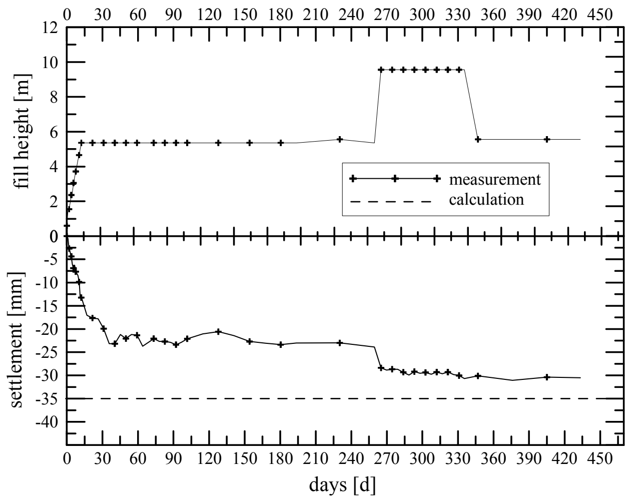

Figure 14. Settlements in a section with horizontal geogrid reinforcement on top of the piles.

The settlements in the section with a cement stabilization of the embankment material instead of the geosynthetic reinforcement or a concrete slab are very low (up to 2 mm) due to the very low embankment. Therefore these measurements are not comparable to the settlements shown above.

8 CONCLUSION

According to the experiences during the construction of the railway line Beijing-Tianjin and the experiences in Germany a geosynthetic reinforcement as well as a cement stabilization of the embankment material can be used instead of a concrete slab to guarantee a sufficient load transfer and distribution.

Based on German and international experiences with geogrid-reinforced pile-supported embankments, practical reasons, experimental results and the validity of the analytical model the following recommendations are established:

The center-to-center distance s (see Figure 15) of the piles and the pile diameter d (pile caps) should be chosen as follows:

- $(s - d) \leq 3.0$ m: in the case of static loads
- $(s - d) \leq 2.5$ m: in the case of heavy live loads
- $d / s \geq 0.15$
- $(s - d) \leq 1.4 (h - z)$

The distance between the reinforcement layer and the plane of the pile/column/wall heads should be as small as possible, in order to achieve maximum efficiency of the geogrid membrane. However, it is recommended to have a safe distance z (interlayer) between the lowest reinforcement and the pile heads in order to prevent a structural damage of the reinforcement because of shearing at the edge of the pile heads:

- maximum two reinforcement layers
- $h_{geo} \leq 0.15$ m for single layer reinforcement
- $h_{geo} \leq 0.30$ m for two layers reinforcement
- for two layers the distance between the geogrid layers should be 15 to 30 cm
- design value of the tensile strength $R_{Bd} \geq 30$ kN/m; ultimate strain ≤ 12 %.
- overlapping is generally allowed, but only just above the pile (caps) and only in the secondary bearing direction; length of overlapping ≥ d.

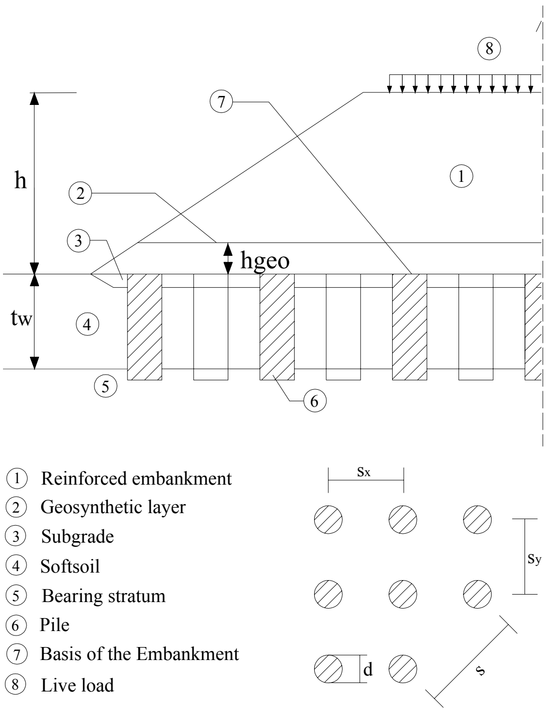

Figure 15. Geosynthetic-reinforced pile supported embankment (GPE) – Definition of parameters

9 REFERENCES

Alexiew, D. & Vogel, W. 2001. Railroads on piled embankments in Germany: Milestone projects, Landmarks in Earth Reinforcements. In Ochiai et al. (eds), Swets & Zeitlinger: 185-190.

Empfehlung 6.9 2003. Bewehrte Erdkörper auf punkt- oder linienförmigen Traggliedern. *Kapitel 6.9 für die Empfehlungen für Bewehrungen aus Geokunststoffen, EBGEO, DGGT (German Geotechnical Society)*, draft.

Heitz, C. & Kempfert, H.-G. 2007. Bewehrte Erdkörper über Pfählen unter ruhender und nichtruhender Belastung. *Bauingenieur*, Band 82: 380 – 387.

Kempfert, H.-G., Goebel, C., Alexiew, D. & Heitz, C. 2004. German recommendations for reinforced embankments on pile-similar elements. *Third European Geosynthetic Conference, DGGT (German Geotechnical Society)*, Volume 1: 279-285.

Kempfert, H.-G. & Raithel, M. 2005. Soil Improvement and Foundation Systems with Encased Columns and Reinforced Bearing Layers. In "Ground Improvement Case Histories" Ed. Buddhima Indraratna and Chu Jian. Elsevier B.V.

Raithel, M., Kirchner, A. & Kneissl, A. 2006.Gründung der Hochgeschwindigkeits-Teststrecke Beijing-Tianjin auf Grundlage von vergleichenden Probebelastungen an Großbohrpfählen, Rammpfählen und SOB-Pfählen. In Vorträge der Baugrundtagung 2006 in Bremen, *DGGT (German Geotechnical Society)*.

Raithel, M., Kirchner, A. & Kempfert, H.-G. 2008. German Recommendations for reinforced Embankments on Pile-similar elements. *Proceeding of the 4th Asian Regional Conference on Geosynthetics*, June 17 - 20, Shanghai.

Zaeske, D. 2001. Zur Wirkungsweise von unbewehrten und bewehrten mineralischen Tragschichten über pfahlartigen Gründungselementen. *Schriftenreihe Geotechnik*, Universität Kassel, Heft 10.

Zaeske, D. & Kempfert, H.-G. 2002. Berechnung und Wirkungsweise von unbewehrten und bewehrten mineralischen Tragschichten auf punkt- und linienförmigen Traggliedern. *Bauingenieur*, Band 77.