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Piled embankments: Overview of methods and significant case studies

Remblais sur pieux: Aperçu de méthodes et cas d'études significatifs

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ABSTRACT
Embankments on soft subsoil supported by piles or columns of different type and high-strength horizontal "bridging" geosynthetic reinforcement on top of them have important advantages compared to "conventional" embankment foundation directly on the soft soil. Because the loads are being transferred to a firm substratum below the soft soil layer no settlement takes place, 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. Due to these advantages the application of such solutions is growing permanently worldwide. A short critical overview of analytical design procedures is presented pointing out their plausibility and reliability. Some selected specific projects of geogrid-reinforced systems on piles or columns are shortly described and analyzed, pointing out new moments and lessons learned.

RÉSUMÉ
Les remblais sur des sous-sols mous portés par des pieux ou des colonnes de différents types et des géosynthétiques de renforcement à haut module présentent de nombreux avantages par rapport aux solutions traditionnelles » (directement sur le sol mou). Les charges sont directement transférées sur le substratum, il n'y a donc aucun tassement, il n'est donc pas nécessaire d'attendre la consolidation, il n'y a pas d'apport/retrait de remblais supplémentaires afin d'accélérer la consolidation ou de compenser le tassement. Pour ces multiples raisons, ce type de solutions est en pleine croissance dans le monde entier. Un court aperçu de méthodes de dimensionnement analytiques est présenté, insistant sur leur pertinence et leur fiabilité. Quelques projets spécifiques présentant des renforcements en géogrille sur pieux ou colonnes seront brièvement décrits et analysés insistant sur les nouveautés et l'expérience acquise.

1 GENERAL IDEA, PRINCIPLES AND SOME REINFORCEMENT BASICS

The general concept of reinforced piled embankmentes is shown in Figure 1 (modified from BS 8006 (1995)). All embankment loads are transferred via the vertical bearing elements (piles, columns etc.) through the soft soil into a firm substratum below. For bridging the space from pile to pile the embankment fill is supported by horizontal geosynthetic reinforcement although some arching occurs in the fill. Today geosynthetic reinforcement with up to 1800 kN/m ultimate tensile strength is available, therefore it is not a problem to control bearing capacity and serviceability even for huge net spacings (s-a) (Fig. 1).

The use of different polymers allows a precise optimal choice of stress-strain behavior of geosynthetic reinforcement for both short-term (compare e.g. graphs on Fig. 2) and long-term conditions.

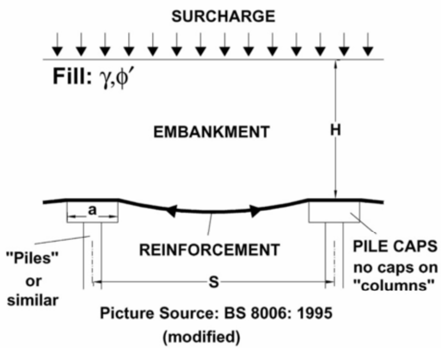

Figure 1. General idea of reinforced embankments on piles

Note, that the short-term strain can be of less importance than the long-term additional creep strain. The first one can be compensated during construction, the second one occurs in the post-construction stage under traffic over the entire design life and cannot be compensated (Alexiew 2004).

Additionally, the horizontal outward spreading force (often significant) in the zone beneath the slopes has to be taken over by the reinforcement; this is beyond the scope of this paper.

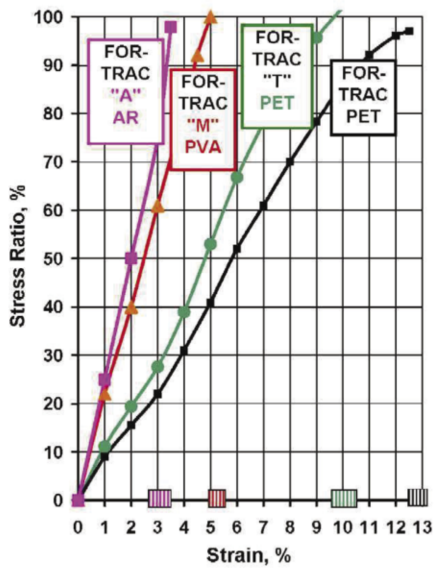

Figure 2. Influence of the polymer used on the tensile force-strain behavior of similar geogrid "families"

2 SHORT OVERVIEW OF DESIGN METHODS

Starting in 1986 different analytical calculation methods have been developed and suggested. The application of numerical 2-D and 3-D analyses is increasing. They often tend to underestimate the required geosynthetic strength. Numerical methods are beyond the scope of this paper.

There are two focal points in any analytical procedure:

- what is the stress redistribution in the embankment body: which part of the load is born directly by the piles due to "arching", and which part has to be taken over by the geosynthetic reinforcement between the piles (Fig. 1)

- what are the required stress-strain behavior and design strength of the geosynthetic reinforcement itself.

Note: for all analytical procedures listed below only a non-cohesive (frictional) embankment fill is assumed (see section 3.2 for an alternative solution). For more details see Alexiew (2004).

2.1 *The so-called "Guido Method" (Fig. 3)*

A very simplified approach. The reinforcement has to bear only small pyramids. The original paper (Guido 1987) has nothing to do with that approach. Pyramids geometry is always the same independent of the fill (i.e. same design results for fine sand and crushed rock – not realistic!). Because the pyramids are very flat, surcharge on embankment is rarely taken into account (risky!). No standards based on this method. Severe serviceability problems have been registered for some projects based on this design approach.

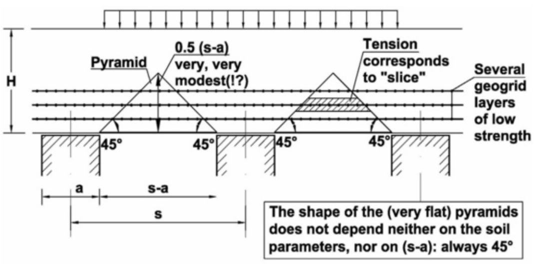

Figure 3. The so-called "Guido Method"

2.2 *The "Swedish Method" (Fig. 4)*

First suggestion in Carlsson (1987), recent suggestions in Rogbeck et al (2000). Simplified approach: always pyramids of 75° wall inclination, independent of type and strength of embankment fill (not realistic!). Better than the "Guido Method": pyramids can reach the embankment surface and thus include surcharge. Dimensioning of reinforcement based on the "membrane theory" similar to Fig. 1. Reinforcement concentrated in one layer on top of the piles. The method is popular mainly in Scandinavia.

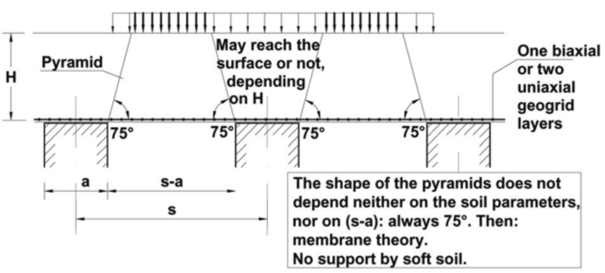

Figure 4. The "Swedish Method"

2.3 *The "British Standard 8006 Method" (Fig. 5)*

First approaches explained in John (1987), further developments shown e.g. in Jones et al (1990), finally fixed as Standard in 1995. 3-D-arching assumption in the embankment fill: always a semi-sphere, independent of type and strength of fill (not realistic!). It cuts the embankment surface rarely, thus traffic load hardly ever taken into account. "Membrane theory" for the tensile force in reinforcement (Fig. 1). Reinforcement concentrated in one layer on top of piles. No support of reinforcement upward counterpressure from the soft soil between the piles: "free hanging system". Results inconsistent for levels close to 1.4 (s-a) (top of "dome"). Popular official standard procedure despite some inadequacy.

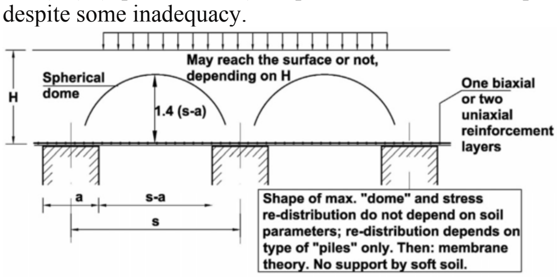

Figure 5. The "BS 8006 Method"

2.4 *The "Older German Method" (Fig. 6)*

The development started in 1992-1993. The independence of stress redistribution in the embankment from its shear strength assumed e.g. in the "Guido Method", the prototype of the "Swedish Method" and even in the BS 8006 (draft) seemed not acceptable. Therefore the stress-redistribution according to Hewlett & Randolph (1988) taking the fill strength into account (!) was combined with the "membrane theory" in BS 8006 for dimensioning of the reinforcement. Some counterpressure from the soft soil onto reinforcement was allowed to be considered based on the soft soil strength (Kempfert et al 1997), (Kempfert et al 1999). The method was widely accepted for many projects; extensive measurement programs were applied (Alexiew & Vogel 2001) confirming e.g. the membrane theory.

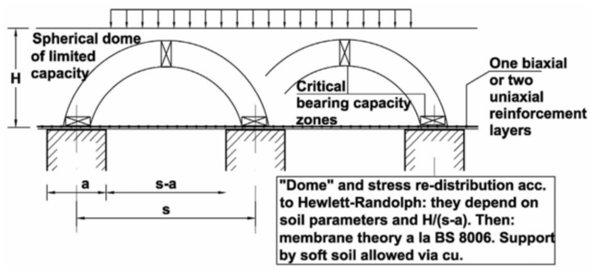

Figure 6. The "Older German Method"

2.5 *The "New German Method" (Fig. 7)*

The development started in 1995. Focal points were to improve the stress redistribution model for the embankment body and to find a way for a reasonable consideration of a possible upward soft soil counterpressure between the piles (Kempfert et al (1999), Zaeske (2001)) (good work). The draft for a new chapter in EBGEO (1997) is ready. It includes a new "multi-shell arching" theory and a strain-related counterpressure. Only one or maximum two strong reinforcement layers directly on top of piles are strongly recommended. Because the soft soil counterpressure is of great influence on the results (reinforcement tension), caution is advised: e.g. sinking of ground water level could eliminate any counterpressure. For more details see Kempfert et al (2003).

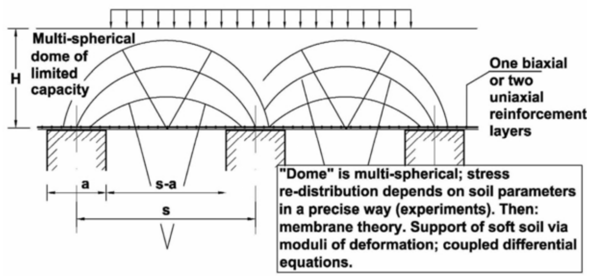

Figure 7. The "New German Method"

3 OVERVIEW OF SOME INTERESTING PROJECTS

Due to the lack of place only short descriptions of selected projects are given. Each of them includes something new or a specific solution. More projects are described e.g. in Alexiew (2004), Heitz et al (2005).

3.1 *Gasoline station, "Shell" Bulgaria, Sofia, 1998*

Very flat system due to existing surrounding infrastructure and high GWL; only one single layer of relatively strong 5 m wide biaxial geogrid overlapped just on top of piles (Fig. 8). In fact a "low-cost"-project: huge pile spacing, no pile caps despite the heavy surcharge by gasoline trucks. Very careful construction, heavy compaction starting with the first fill layer of 30 cm, direct supervision by the project engineer (the author). No deformations under traffic after 6 years.

Key findings: Single-layered strong wide biaxial geogrids are a good solution they have to overlap just on top of piles ensuring load transfer and saving system height; intensive fill compaction from the same beginning is important!

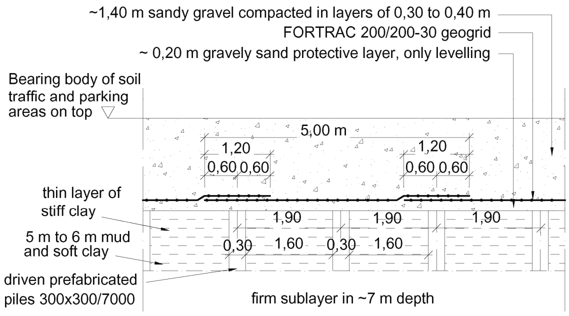

Figure 8. Cross-Section "Shell-Station" in Sofia

3.2 *Project Crossing River Laje at Chapadao, Ferronorte Rail, Brazil, 1998*

High embankment, very heavy cargo-trains, use of local cohesive lateritic soil (modest φ, high cohesion), slim piles with caps (Fig. 9). One single layer of customized "semi-biaxial" 5 m wide flexible geogrid with 400 kN/m in roll direction and 150 kN/m in cross-roll direction, unrolled perpendicularly to embankment axis. "Old German Method" used for design; the author applied an "equivalent φ" to take cohesion into account, which is not foreseen in the analytical procedures available today.

Key findings: cohesive soils can be successfully used for embankments on piles; using "equivalent φ" for design considering also cohesion seems to be acceptable, but attention should be paid regarding the final design value; customized "semi-biaxial" reinforcement combined with an appropriate jointing technique can save costs.

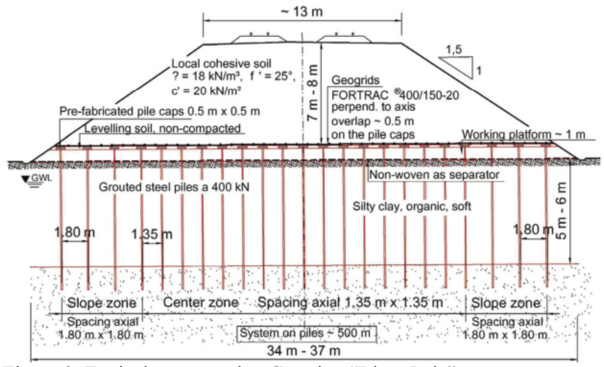

Figure 9. Typical cross-section Crossing "River Laje"

3.3 *Project A 63 Selby Bypass, British Highway Authority, UK, 2002-2003*

The height of the motorway embankments amounts up to 12 m; construction and post-construction deformations including both vertical settlements and horizontal strains were strictly limited. The subsoil over the stretch consists of silts, clays and peat.

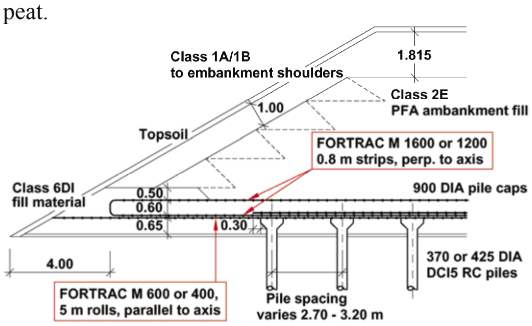

Figure 10. A63 Selby Bypass: typical cross-section

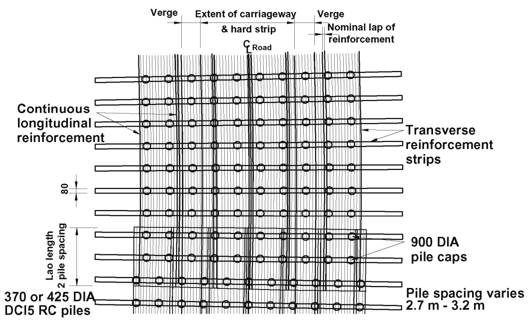

Figure 11. A 63 Selby Bypass: typical layout of reinforcement

To save costs very large pile spacing and small pile caps were chosen (Fig. 10). High spreading forces and horizontal sensitivity of the slim piles are specific for that project. This resulted in the need of high-strength, high-tensile-stiffness geogrids. Design was performed according to BS 8006 (1995) with modifications for the distribution of load between two different perpendicular reinforcements. The solution comprises very strong low-strain geogrid "strips" of geogrids Fortrac® 1600 M and 1200 M with up to 1600 kN/m and only 5% ultimate strain, which were installed perpendicularly to road axis, and "full area" reinforcement from 5 m wide uniaxial geogrids Fortrac® 400 and 600 with up to 600 kN/m parallel to the road direction (Fig. 10, 11 & 12). Thus, an optimized "mixed" reinforcement system was created. A measurement program was applied to register the deflections and horizontal outward displacements. Until now no deflections or displacements beyond the acceptable values have been registered. For more details see Wood et al (2004).

Key findings: combining geogrids from different polymers helps to optimize the solution using precisely the strengths and strains needed for the corresponding direction; high-strength geogrids with high tensile stiffness reduced to "strips" on top of piles perpendicularly to the embankment axis can be a feasible solution.

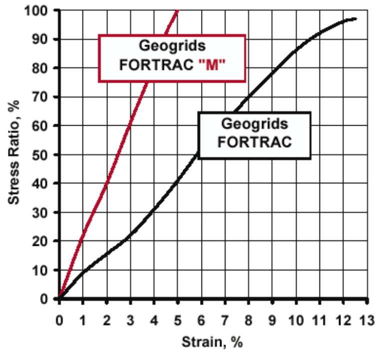

Figure 12. A 63 Selby Bypass typical normalized stress-strain curves for the geogrids used

3.4 *Project "Büchen", German Rail (DB), Rail link Berlin-Hamburg, Section PRA 4, Germany, 2003*

On the double rail link Berlin-Hamburg a stretch on soft soil near the town of Büchen had to be upgraded in 2003 to allow a higher train speed. Both bearing capacity and serviceability had to be guaranteed. The system (Fig. 13) is very flat, and is worldwide the thinnest structure on piles for railroads. The reconstruction was planned in two "halves" connecting them by the geogrid installed perpendicularly to rail axis (Fig.13). Due to the low height of embankment spreading loads were not an issue: the geogrids cross to embankment axis had not to be stronger than the axis-parallel ones. Mixed-in-place columns were chosen as vertical bearing elements. Cemented local soils were used for the embankment body. Uniaxial geogrids Fortrac® 400/30-30 M were chosen for both directions for two reasons: due to their high short- and long-term tensile stiffness and due to their high alkaline resistance as well because of the high alkalinity of the cemented embankment soil. Due to the flexibility of the geogrids, wrapping-back with a small radius at the edges of embankment was not a problem. The system is since a year under traffic without any serviceability problems (Raithel et al 2004).

Key findings: even extremely flat railroad embankments on piles can be built successfully; the combination of cemented local soils and appropriate geogrids has proved to be successful.

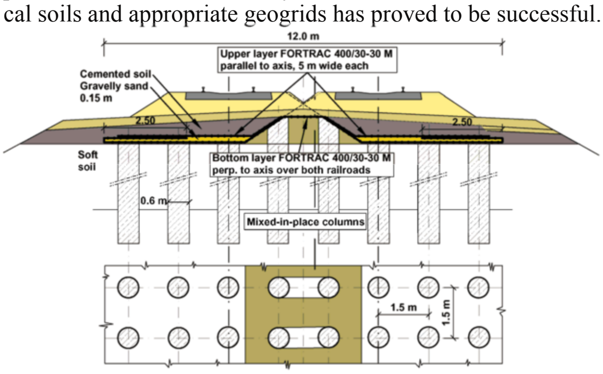

Figure 13: Typical cross-section "Büchen"; the bottom geogrid is installed over the entire width, the upper ones separately in the left and right half

4 FINAL REMARKS

Reinforced embankments on piles or columns have reached the stage of maturity. Huge experience is available regarding design procedures, construction and (registered) behaviour. The range of geosynthetic reinforcements and different row materials available today eliminates any limitation for their use in such systems. It is financially efficient to maximize pile spacing and to use stronger geosynthetic reinforcement in only one to two layers.

In case of any doubt regarding bearing capacity or serviceability in the stage of design: use stronger reinforcement. The costs are negligible in relation to possible reconstruction costs. Some failed or highly deformed structures are known, but beyond the scope of this paper.

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