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GEOSINTETICI NELLE COSTRUZIONI DI TERRA

Nuovi orientamenti per i rilevati rinforzati e le discariche controllate

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PILED EMBANKMENT DESIGN: METHODS AND CASE STUDIES

PROGETTAZIONE DI RILEVATI POGGIATI SU PALI: METODOLOGIE ED ESEMPI DI CASI REALI

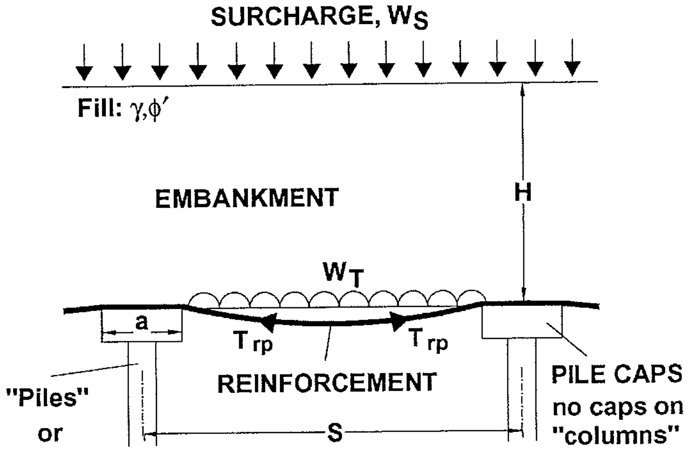
1. Introduction

Embankments on soft subsoil supported by piles or similar elements and high-strength geosynthetic reinforcement on top of them have important advantages compared to "conventional" embankment foundation: 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. The application of such solutions is growing recently worldwide.
Corresponding design procedures have meantime more than 10 years of history going through significant development, scientific and verification efforts across Europe.
A critical overview of these procedures is presented pointing out the increasing precision and reliability incl. the recent state-of-the-art in Germany.
Some typical interesting projects during the last about 10 years are shortly described and discussed including both railroad and road applications, different concepts and geosynthetic reinforcements, measurement programs and experience.

2. General idea, principles and some reinforcement basics

The general concept is shown in Figure 1 (modified from (BS 8006 1995)). All embankment loads are transferred via the vertical supporting bearing elements (piles of any kind, stone columns, high-strength geosynthetics encased sand columns etc., further herein only "piles" for simplicity) directly to the firm substratum (usually in a depth of 10 to 30 m). For bridging the space from pile to pile the embankment soil needs additional support by a horizontal geosynthetic reinforcement although some arching occurs. Generally, the larger is the "net span" ((s-a) in Figure 1) to be bridged, the higher are the requirements on the geosynthetic reinforcement concerning both the design strength (higher!) and the strain, especially the creep strain (lower!).

Today geosynthetic reinforcement with up to 1600 kN/m ultimate tensile strength is available, thus strength and strain control is strictly speaking not an issue.



Picture Source: BS 8006: 1995 (modified)

Fig. 1 - General idea of reinforced embankments on piles.

The use of different polymers allows for a precise appropriate choice of stress-strain behaviour for both short-term and long-term conditions (compare e.g. graphs on Fig. 2, showing so called isochronous curves for the relation tensile force-strain-time).

Note, that the short-term strain is 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 over the entire design life and cannot be compensated (Fig. 3). In any case time- and stage-dependent analysis is strongly recommended. Additionally, the horizontal outward spreading force in the zone beneath the slopes has to be considered; this is beyond the scope of this paper.

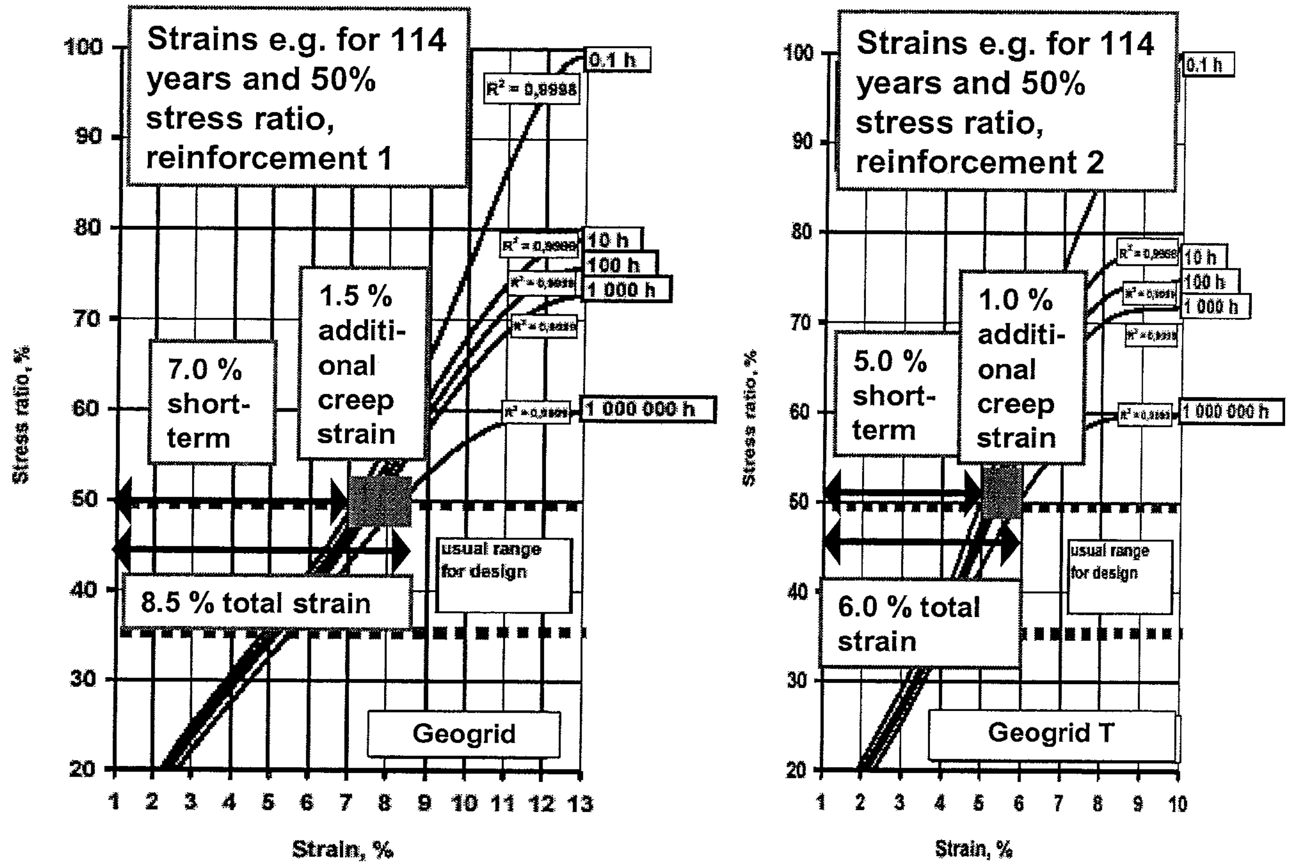


Fig. 2 – Isochrones: short- and long-term and total strain depending on load and reinforcement type.

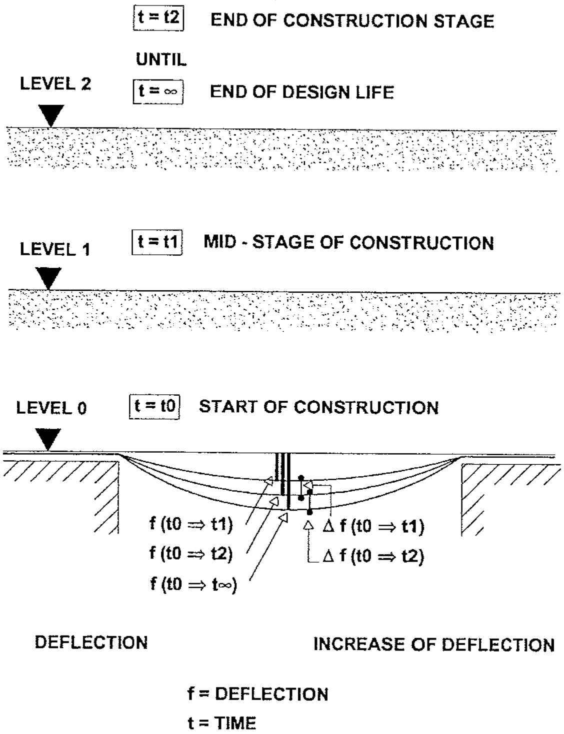


Fig. 3 – Stage time dependent analysis: the post-construction creep strain often controls the design.

3. Overview of some design methods

Starting from about 1985 different analytical calculation methods have been developed and suggested. The older ones are relatively simplified, the recent ones more sophisticated and precise. Despite these analytical procedures during the last years the application of numerical 2-D and 3-D analyses is increasing step by step. One should keep in mind, that beside their known advantages such procedures are very sensitive to the input geotechnical parameters, constitutive rules assumptions, experience of the project engineer with numerical software etc.. These methods are beyond the scope of this paper.

There are mainly two focal points in any analytical procedure:
- stress-strain redistribution in the embankment body (i.e. which part of the load reaches directly the top of piles due to "arching", and which part should be taken over by the geosynthetics reinforcement between the piles (Fig. 1));
- stress-strain 2-D- and 3-D-behaviour of the geosynthetics reinforcement itself.

The following general relationship are always valid:
- the higher is the shear resistance of embankment soil (huge influence),
- the higher is the ratio H/(s-a) in Fig. 1,

- the larger is the pile top resp. cap,
- the higher is the upward counterpressure from the soft soil between the piles on the reinforcement ("soil reaction / soil embadment pressure", so far as available) below the "hanging" deformed reinforcement (Fig. 1),

the lower are the required tensile strength and tensile moduli of geosynthetic reinforcement.

A short, more or less chronological, overview of design methods will be presented hereafter.

3.1 The "Guido Method" (Fig. 4)

Very simplified approach. The reinforcement is dimensioned to bear only very small pyramids as depicted. Although being often cited as "Guido Method", the original paper (Guido 1987) has nothing to do with that approach. Not supported by scientific research or comparative analyses. Pyramids have always the same shape not depending on the strength (angle of internal friction) of embankment soil. For all cases known only a very coarse high-strength fill (φ > 45°) has been recommended and applied. No standards based on this method. It seems to be risky (Kempton et al 1998, Russel & Pierpoint 1997); serviceability problems has been registered.

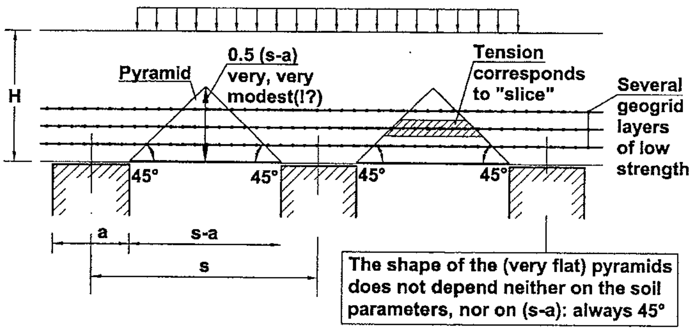


Fig. 4 - The so-called "Guido Method.

3.2 The "Swedish Method" (Fig. 5)

First suggestion in Carlsson (1987), recent suggestions in Rogbeck et al (1998), Rogbeck et al (2000). Simplified approach; the reinforcement has to bear always pyramids of 75° wall inclination, not depending on φ of embankment fill. In any case more careful than the "Guido Method"; pyramids can cut the embankment surface and thus include the traffic surcharge. Dimensioning of reinforcement based on the "membrane theory similar to Fig. 1. No standard based on that method yet. Resulting reinforcement 2 to 3 times stronger than according to the "Guido Method".

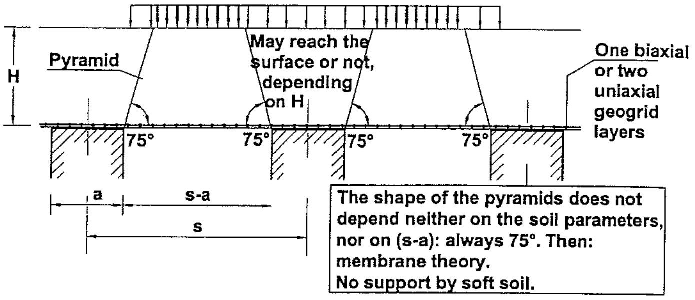


Fig. 5 – The "Swedish Method".

3.3 The "British Standard 8006 Method" (Fig. 6)

First approaches explained in John (1987), further developments shown e.g. in Jones et al (1990), finally fixed as Standard in 1995. More sophisticated than "Guido Method" and "Swedish Method". Simplified 3D-arching assumption in the embankment soil: always a semi-sphere, not depending on the embankment material (say, the same results for fine sands and crushed gravel!). The relatively flat semi-sphere cuts the embankment surface rarely, thus traffic load hardly ever taken into account. "Membrane theory" for the tensile force in reinforcement loaded by the soil below the "arch". No upward counterpressure between the piles even e.g. for relatively stiff clays. Popular official standard procedure despite some "weak" points. For the interested reader we recommend additionally Lawson (2001).

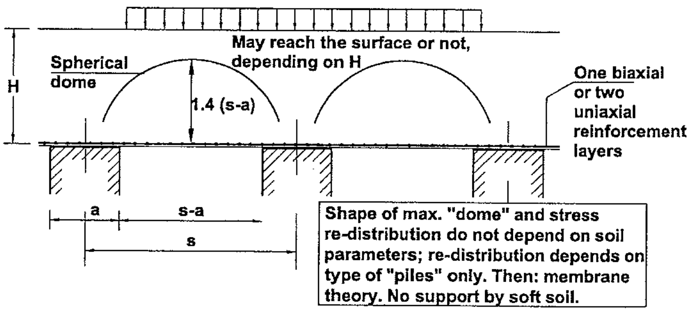


Fig. 6 – The "BS 8006 Method".

3.4 The "Older German Method" (Fig. 7)

Development started in 1992-1993, the Draft of BS 8006 was known in Germany at that time. The independence of stress redistribution in the embankment from its shear strength assumed e.g. in the "Guido Method", the "Swedish Method" (draft) and the BS 8006 was not accepted by geotechnical engineers in Germany incl. the author of the present paper. It was decided to combine the stress-redistribution according to Hewlett & Randolph (1988) (which depends not only on H/(s-a) but on φ of the embankment soil as well (Fig. 7)) to estimate the load to be born by reinforcement with the "membrane theory" according to BS 8006 for dimensioning of the reinforcement itself. Additional efforts were made to correct a small error in Hewlett & Randolph (1988), to take into account some upward counterpressure of soft soil between the piles and

to establish basic recommendations for minimum reinforcement and construction procedures; for more details see e.g. Vogel (1995), Kempfert et al (1997), Kempfert et al (1999), Alexiew & Gartung (1999), Alexiew & Vogel (2001).
The method was widely accepted for many projects; extensive measurement programs were applied (Alexiew & Gartung 1999, Alexiew & Vogel 2001).

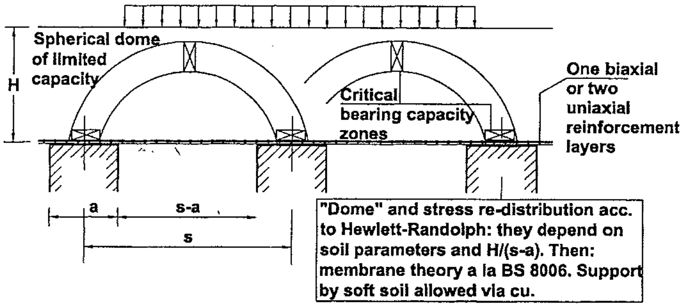


Fig. 7 – The "Older German Method".

3.5 *The "New German Method" (Fig. 8)*

Development started about 1996. Main ideas were to improve the load redistribution theory for the embankment body and to find a way for a reasonable consideration of a possible upward soft soil counterpressure between the piles. Series of 1:3 well instrumented model tests were performed for verification (Kempfert et al 1999, Zaeske 2001 (good work)). The efforts were successful. After additional work in 2000 to 2002 the draft for a new chapter in EBGEO (1997) is almost ready. Included is a new "multi-shell arching" theory, calculation of tensile forces in the reinforcement taking into account the soft soil oedometric modulus, strain-related counterpressure, the recommendation to use maximum two high-strength layers of reinforcement on top of piles etc.

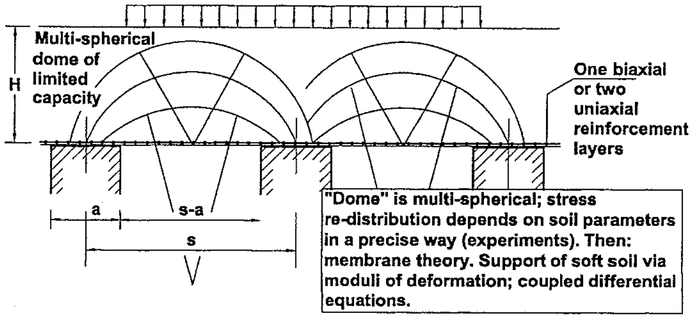


Fig. 8 – The "New German Method".

4. Overview of some 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. For details of some of the projects see Alexiew & Gartung (1999), Alexiew, Pohlmann & Lieberenz (2000), Alexiew, Sobolewski & Pohlmann (2000), Alexiew & Vogel (2001).

4.1 *Project Werder-Brandenburg, German Rail, 1994*

Officially a reconstruction, de facto complete rebuilding of a long old stretch to allow for train speed of 160 km/h on extremely soft thick subsoil layers (Fig. 9). Designed acc. to the "Old German Method" with high hidden "safeties" at that "young" time. Three layers of relatively strong biaxial PET-Geogrid used. Accompanied by the most expansive and long-lasting measurement program known for such structures. Good performance until now. Lessons: tilting tendency of cap plates on top of very slim iron piles, some surprising pile settlements (Fig. 10), membrane theory for reinforcement confirmed (important!)! Measurements are ongoing.

RAIL LINK RECONSTRUCTION MAGDEBURG-BERLIN
STRETCH WERDER-BRANDENBURG
GEOGRIDS FORTRAC R 150/150-30
5 M WIDE; 3 LAYERS, INCL: SPECIAL PREFABRICATED
(IN PLANT) ARAMID SEWN JOINT
TOTAL STRETCH LENGTH 1,512 KM

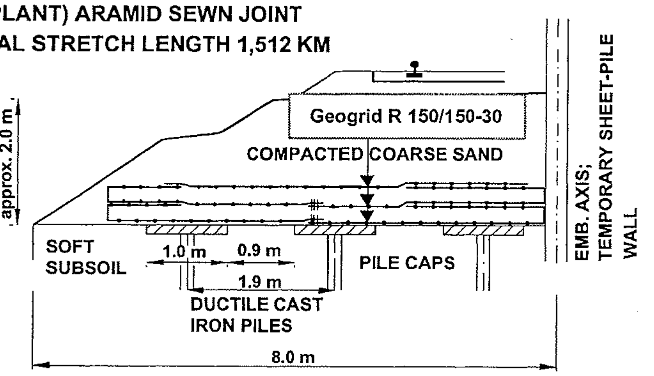


Fig. 9 – Cross-section of the project Werder-Brandenburg.

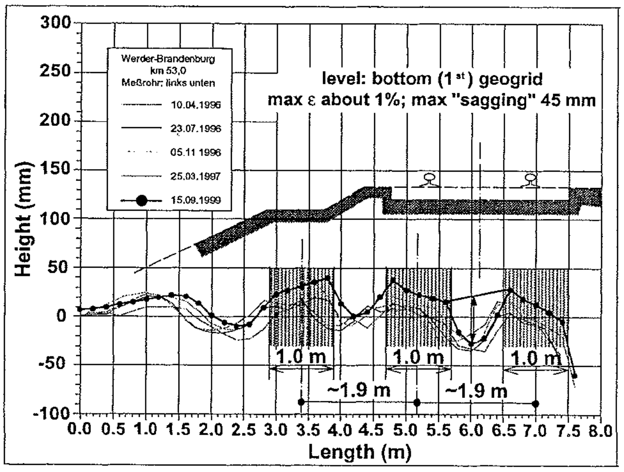


Fig. 10 - Werder-Brandenburg: typical deformed shape at the level of bottom geogrid and caps; note the different scales (hor. axis [m], vert. axis [mm])!

4.2 *Project Rathenow (Körgraben), German Rail, 1997*

Section of a new stretch for the ICE (German high speed train), very flat system, very strict limitation of any deformation, concrete slab-track. Design resulted in high-strength extremely low-strain aramid (AR)-geogrids in two layers (Fig. 11), "Old German Method" applied. Measurement program, 1 month simulation of ICE-drives using special dynamic loading equipment, 4 months under added 2 m of embankment, dynamic measurements under ICE test-drives with up to 300 km/h. Excellent performance, less than 20 mm reinforcement deflection in the bottom layer and less than 10 mm in upper layer. Lessons: even very sensitive systems can be built using appropriate reinforcement.

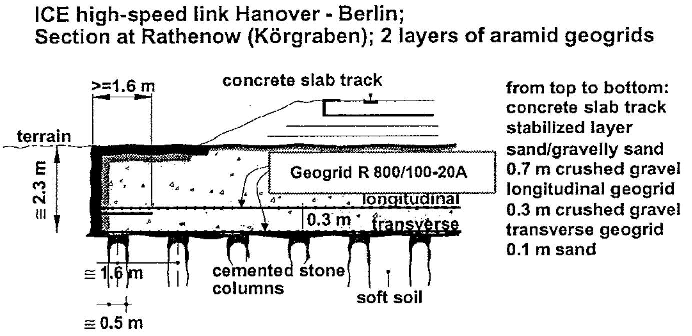


Fig. 11 – Project Rathenow, typical cross-section.

4.3 Gasoline station, "Shell" Bulgaria, Sofia, 1998

Very flat system due to existing surrounding infrastructure and high GWL; due to that one single layer of relatively strong 5 m wide biaxial geogrid overlapped just on top of piles (Fig. 12). In fact a "low-cost"-project: huge piles spacing, no pile caps despite the heavy surcharge by gasoline trucks. Very careful construction, heavy compaction starting with the first soil layer of 30 cm, direct supervision by the project engineer (the author). No deformations under traffic after 5 years. Lessons: Strong wide biaxial geogrids are a good solution to fit overlapping just on top of piles to ensure load transfer and to save system height; intensive soil compaction from the same beginning is important; (strong) one-layer systems are feasible; early "synchronisation" of piles pattern and geosynthetic reinforcement is very important ("project interface").

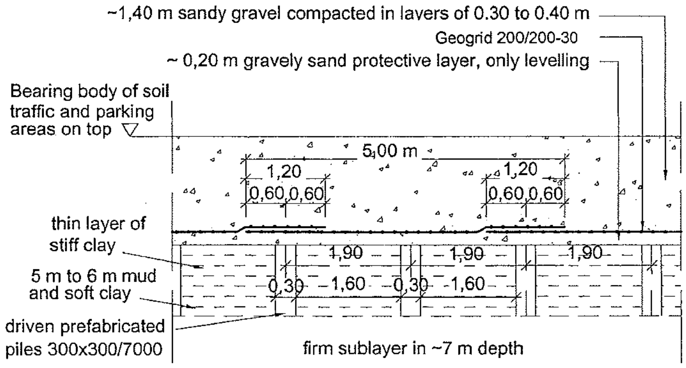


Fig. 12 – Cross-section "Shell-Station" in Sofia.

4.4 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). Set on very slim piles with caps (Fig. 13). One single layer of customized "semi-biaxial" 5 m wide geogrid with 400 kN/m in roll direction and 150 kN/m in cross-roll direction, unrolled perpendicular to embankment axis. "Old German Method" for design; the author applied an "equivalent φ" to take cohesion into account, which is not foreseen in the analytical procedures until today (see above, Chapter 3).

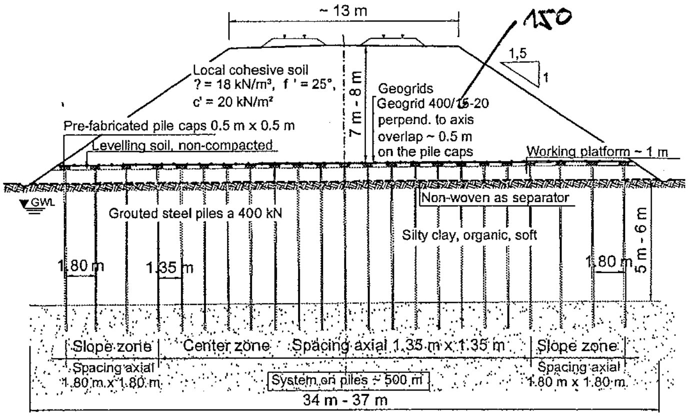


Fig. 13 – Typical cross-section Crossing River Laje.

Good performance after 4 years under traffic. Lessons: cohesive soils can be successfully used for embankments on piles; using "equivalent φ" for design seems to be acceptable; customized "semi-biaxial" reinforcement can save costs.

4.5 Project Harper-Mühlenbach, German rail, 1999

Upgrading an old stretch for 160 km/h; wider and stabilized embankments were required. Solution: cut the upper half of old embankment away, install cemented stone columns, install geogrid on top, build up the upper half again using geogrid-reinforced oversteep slopes on both sides to ensure a sufficient width of top of embankment. First careful application of the "New German Method" for design to take upward counterpressure between the columns from old embankment into account. First certification of a combined system "embankment on pile / oversteep slopes" by the German Railroad Supervising Authority (EBA). Good performance yet. Measurement program showing nearly no deformations at the reinforcement level and of the columns. Lessons: combined systems as this one are feasible for upgrading older railroads; assuming some upward counterpressure from old embankment on reinforcement saves costs. Note the prediction: the latter should be guaranteed for the entire design life (100 years in Germany); it is an important point for discussions, because e.g. a decrease of GWL could eliminate the counterpressure.

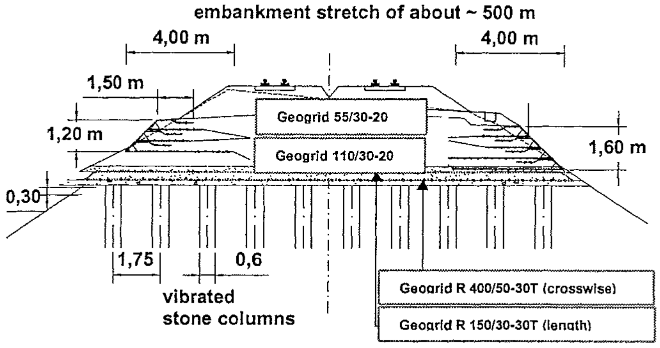


Fig. 14 – Typical cross-section "Harper Mühlenbach".

4.6 *Project Selby Bypass, British Highway Authority, UK, 2002*

Height of embankments up to 12 m, strict limitations of post-construction deformations, use of fly ash for the embankment core. Huge pile spacings with modest pile caps (Fig. 15), relatively slim cast-in-place piles. Very high spreading forces combined with horizontal load sensitivity of piles. Design acc. to the "BS 8006" with some modifications especially of the "membrane theory". Final solution: strong low-strain geogrid "strips" made of PVA (Polyvinylalcohol), having 1600 kN/m ultimate tensile strength (UTS) and 5% ultimate strain, installed on top of pile rows perpendicular to road axis; full area 5 m wide uniaxial PET-geogrids with 400 and 600 kN/m UTS parallel to the road direction; thus, an optimized "mixed" reinforcement system. Measurement program applied, full height of 12 m not reached at that place yet, but low deflections and no horizontal "spreading" displacements until today. Lessons: combining geogrids from different polymers in two different directions helps to optimize the solution using precisely the strengths and strains needed for the corresponding direction and /or section; geogrid reduced to smaller "concentrated" widths on top of piles can be a feasible solution, especially for protecting brittle or slim piles from horizontal displacements.

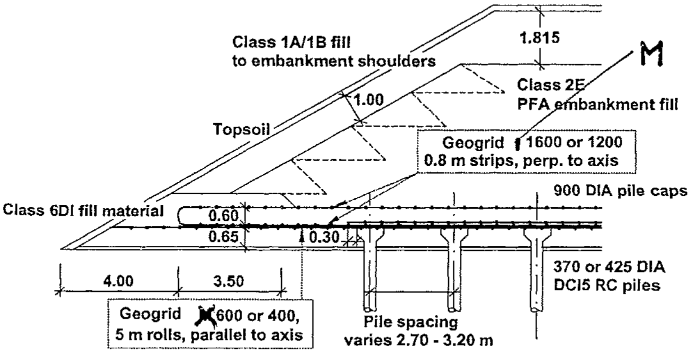


Fig. 15 – Typical cross-section of "Selby Bypass".

5. Final Remarks

Embankments on piles with geosynthetic reinforcement in the base have reached the stage of maturity. Huge experience is available regarding design procedures, construction and (registered) behaviour.

The range of geosynthetic reinforcements available today and different row materials eliminates any technical limitation for their use in such systems. The present experience is that it is financially efficient to maximize pile spacings up to the limit of their bearing capacity and to use stronger geosynthetic reinforcement to compensate that.

The recent German design procedures allow to take into account upward counterpressure from soft subsoil between the piles, thus saves reinforcement costs. Critical issue to be discussed always is: could the latter be lost during 100 years e.g. due to groundwater level sinking.

In case of any doubt regarding bearing capacity or serviceability of piled embankments 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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ABSTRACT

Piled embankment design: methods and case studies

Embankments on soft subsoil supported by piles or similar elements and high-strength geosynthetic 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 Europe.

Corresponding design procedures have meantime more than 10 years of history starting with simplified assumptions, going through significant development, scientific and verification efforts across Europe and resulting in Codes or Draft Codes.

A critical overview of these procedures is presented pointing out the increasing precision and reliability incl. the recent state-of-the-art in Germany.

Some typical projects during the last about 10 years are shortly described and discussed including both railroad and road applications, different concepts and geosynthetic reinforcements, measurement programs and experience.

Finally, short summarizing recommendations are given regarding design principles, calculation and construction procedures.

RIASSUNTO

Progettazione di rilevati poggiati su pali: metodologie ed esempi di casi reali

I rilevati su terreni comprimibili, realizzati con impiego di pali o elementi analoghi in fondazione e geosintetici, caratterizzati da una elevata resistenza a trazione ed aventi funzione di rinforzo, disposti alla base del rilevato, presentano importanti vantaggi rispetto alla soluzione tradizionale; infatti non è necessario attendere l'esaurimento del processo di consolidazione nei terreni di fondazione (l'apertura al traffico è immediata dopo la fine costruzione), non è necessario prevedere maggiori quantità di materiale da costruzione (e la successiva rimozione) per accelerare il decorso dei cedimenti nel tempo, non è necessaria una maggiore quantità di materiale per accomodare i cedimenti, dopo l'apertura al traffico non si verificano ulteriori cedimenti, le interferenze con l'ambiente sono limitate ecc.. Di conseguenza, recentemente, l'impiego di questa soluzione si è progressivamente diffuso nei paesi europei.

Pur tuttavia, i procedimenti ed i metodi di calcolo attualmente disponibili per la progettazione sono stati sviluppati solo nel corso degli ultimi 10 anni; a partire dai primi contributi, tali procedimenti sono stati progressivamente affinati, con lo sviluppo delle ricerche e delle verifiche sperimentali in diversi paesi europei, sino alla redazione di appositi standard o proposte di normative.

In questo contributo, si propone un esame critico di tali metodi, con l'obiettivo di evidenziare il loro progressivo affinamento e l'attuale stato dell'arte in Germania.

Inoltre si descrivono alcune opere realizzate nel corso degli ultimi 10 anni, che possono essere ritenute rappresentative. Tali opere sono relative a progetti in campo ferroviario e stradale, coprono differenti geometrie e tipologie di rinforzi, programmi di monitoraggio e risultati ottenuti.

Infine si riportano alcune considerazioni di sintesi ed alcune raccomandazioni in merito ai criteri di progettazione, ai procedimenti di calcolo ed alle tecniche costruttive.