OVERVIEW OF SOME PIONEERING PROJECTS USING INNOVATIVE REINFORCEMENT

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ABSTRACT

The paper includes an overview of some pioneering projects using innovative geosynthetic reinforcement during the last about 15 years. The focal point is the application of engineered high-strength low-strain reinforcements for specific projects with non-trivial requirements in terms of tensile forces and strain limitations. For the case studies presented the engineering problem faced is described, the requirements to be met, the engineering philosophy, the final optimized solution and the reinforcements used (most of them developed and produced for the cases under discussion). All these cases comprise solutions, products and to some extent design procedures being worldwide novelties proved to be successful. They are presented in chronological order. The first case ("B180 Eisleben") deals with bridging a huge sinkhole on a German highway developing and using for the first time worldwide geogrids from Aramid (AR) with an ultimate tensile strength (UTS) of 1200 kN/m at 3% strain only. The second case ("Böschistobel") is a landfill in the Austrian mountains where AR-Geogrids of 550 and 1200 kN/m UTS were used to ensure the local and global stability at a low level of deformations. The third case ("Körgraben at Rathenow") describes a flat embankment on piles for a new super-express (ICE) stretch of DB (German Rail) using AR-Geogrids with 800 kN/m UTS to meet the stringent deformation limitations. The fourth case ("Einöd") describes the superelevation of an existing landfill to increase its capacity. To ensure the stability and low deformations of the new waste fill in an aggressive environment uni- and biaxial PVA-Geogrids with UTS from 150 to 900 kN/m were developed and used for the first time worldwide. The fifth case ("Gröbers") deals with bridging sinkholes provoked by former mining for a super-express railroad in Germany using combined geogrids from Aramid (AR) and Polyvinylalcohol (PVA) together with stabilized soils and a warning geotextile-based system. The solution met severe requirements in terms of safety, bearing capacity and limitation of deformations of any type.

Keywords: Case studies, novel geosynthetic reinforcements, sinkholes, piled embankments, landfills

INTRODUCTION

The paper includes a very short overview of some selected (due to brevity) pioneering projects using innovative geosynthetic reinforcement during the last about 15 years. The focal point is the application of engineered high-strength low-strain reinforcements for specific projects with non-trivial requirements in terms of tensile forces and strain limitations. Generally speaking, high-strength low-strain low-creep reinforcement helps to solve problems with any heavy-loaded and/or sensitive to deformations geotechnical structure. Typical examples are geo-systems bridging sinkholes, heavy loaded or sensitive piled embankments, some specific landfills, heavy embankments on very soft soils etc. This short selection is believed to demonstrate some typical examples of the mostly pioneering work done in this area. It focuses on the geotechnical engineering challenges and resulting development and application of geosynthetic reinforcement from Aramid (AR) and Polyvinylalcohol (PVA); they were at the time of introduction (and to some extent still are) new polymers as raw material for geosynthetic reinforcement. Please note that the engineering solutions described herein, the design procedures, the development, production and applications of the corresponding georeinforcements were on the one hand initiated as a response to the increasing requirements on reinforcements due to more and more sophisticated, demanding and critical georeinforced systems, but on the other hand, they opened the door for a number of even more elaborate and seminal engineering solutions.

HIGHWAY B180 AT EISLEBEN

In 1987 a huge sinkhole due to karst caverns in the underground completely destroyed the National Road F180 near Eisleben in Eastern Germany (Alexiew 1997). The funnel was 15 m wide at the surface and 25 m deep. At that time it was just refilled and a temporary diversion built. In 1991 after the German reunification the F180 was re-classified as the Bundesstrasse B180 (National Highway B180); for this German road category a speed of 100 km/h is allowed and often controls planning and design solutions. Due to the quickly increasing traffic and importance of the link it was decided that a reconstruction should be made by a sound and safety engineering solution to putting the “old” alignment into operation again instead of the no longer acceptable diversion.

Intensive discussions between the owner (Federal Road Administration), the consultant, the local geological authority etc resulted into the final specification of the problem as depicted in Fig. 1 and into the safety philosophy described shortly herein; for more details see Alexiew (1997 , 2007).

A reactivated smaller sinkhole funnel would have the shape and position like Zone 2 in Figure 1 and a big one like the Zone 1. The probability of Zone 2 (small funnel) was defined as high and of Zone 1 (big funnel) as low.

The main idea was to save the drivers life (at 100

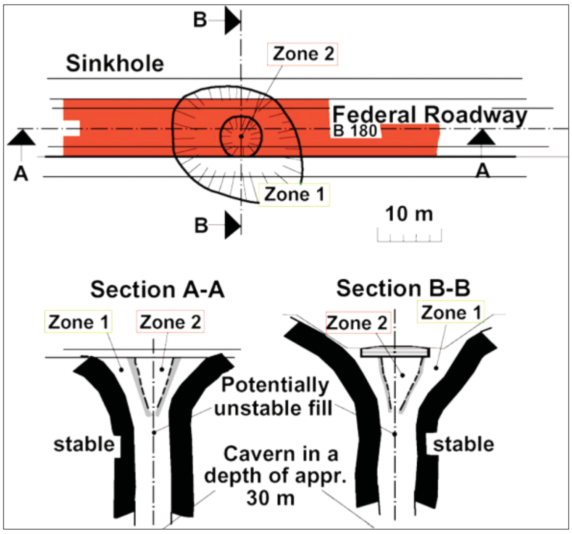


Fig. 1 Geometry and potential sinkhole zones for B180 at Eisleben.

km/hr) keeping the deformations of the Highway B180 at a low level for at least ten minutes. The scheme included a warning system stopping the traffic immediately after a sinkhole reactivation. The allowed deflection of road surface was stringent for the highly probable case of Zone 2 and more tolerant for the huge Zone 1 (Alexiew 1997 , 2007).

Because the critical zone was in a cut the entire system had to be thin (flat).

After intensive discussions a solution with geosynthetic reinforcement was preferred instead of e.g. a RC-plate because of the ductile behavior of geosynthetic-soil systems resulting into a “failure with warning” contrary to the sudden failure of a brittle RC-plate.

At that time the design was performed according to the Draft of BS 8006 (BSI 1995); no other equivalent sound design procedures and/or experience were available (Alexiew, 1997). Fortunately this tool seemed and still seems to be appropriate for analyzing thin systems (but compare the project “Gröbers” herein and EBGEO 2010 for “thicker” etc systems).

During the design analysis the author faced a “small” problem: a georeinforcement meeting the requirements in terms of mobilization of very high tensile force at very low strain (combined with low creep, although the system had to survive for only ten to twenty minutes) was simply not available in the market.

Consequently, a generally new geogrid from Aramid (AR) had to be developed, produced and installed.

The final solution adopted and certified by the Authorities is shown in Fig. 2 and the typical short-term stress-strain graph of the geogrid Fortrac® 1200 A in Fig. 3.

The warning system implemented was generally quite simple and was based on non-corrosive

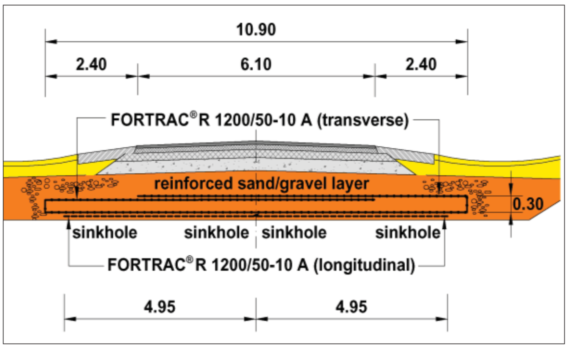


Fig. 2 Schematic cross section of the sinkhole bridging system for B180.

flexible wires connected to contacts in shafts activating stopping traffic signs on both sides of the critical stretch under consideration; for more details see Alexiew (1997 , 2007).

The solution described was built in September 1993 and the Highway B180 opened to traffic in October.

A focal point was the appropriate installation of the geogrid; already in 1993 it was understood that even the best reinforcement will not work in an optimal way if not precisely installed.

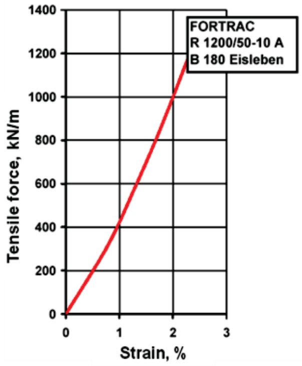


Fig. 3 Typical short-term mechanical behavior of the aramid geogrid developed, produced and installed at B180.

Consequently, a "tensioning" installation beam was developed and used.

In October 2001 (eight years later) in a late afternoon the sinkhole reopened in a quite dramatic way and the next morning had dimensions significantly larger than assumed as per Figure 1. A detailed description can be found in Alexiew (2007).

The system was able to keep all the deformations under traffic small enough to prevent any problem for more than one hour (longer than the design requirements) before it failed spanning a larger sinkhole than assumed in the design stage.

Samples from the geogrid Fortrac® 1200 A were exhumed in situ and tested in 2001 showing in fact no difference to the "virgin" product from 1993 (Alexiew, 2007).

Lessons Learned:

Even a very thin system for bridging voids can be successfully implemented using appropriate geosynthetic reinforcement (arranged properly) together with sound design procedures.

Systems from geosynthetic reinforcement and soils behave in fact in a ductile way experiencing a "failure with warning" which is much safer then "brittle failing" rigid systems.

Engineered customized geosynthetic reinforcement produced to meet project-specific requirements can result into an efficient and safe solution.

Innovative Aspects:

A high-strength low-strain geogrid from Aramid (AR) was developed, produced and implemented successfully for the first time worldwide in a georeinforced system.

Bridging sinkholes by a georeinforced system was used for the first time worldwide for a highway with 100 km/h design speed (a German "Bundesstrasse").

For the first time such a solution was tested and "approved" 1:1 in a "real life" situation.

LANDFILL "BÖSCHISTOBEL"

In 1996 in the Austrian mountains the municipal landfill "Böschistobel" had to be enlarged (heighten) and accordingly modified. One of the challenging aspects of the project was the position of the entire landfill in a slope. This specific geometry and position (Fig. 4) resulted into an insufficient overall sliding stability of the entire waste body as marked in Figure 4. The geomembrane (liner) in the base and on the slope up to the first berm was already installed with its quite low angle of interface friction $\delta=7°$ and the landfill was already filled approximately up to the first berm in Figure 4. For the next section of the slope a textured liner was foreseen with $\delta=14°$.

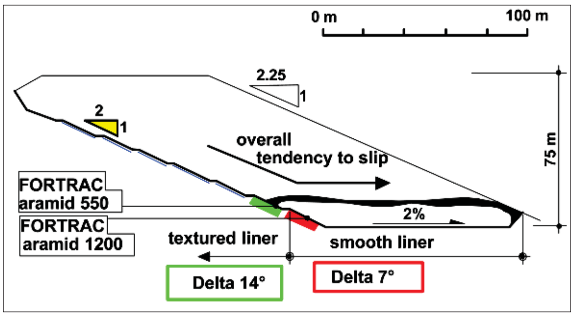


Fig. 4 General scheme of position and geometry of landfill "Böschistobel" and general sliding tendency.

For the previous (lower and flatter, not shown) waste body geometry the stability should be sufficient, but no more for the new (higher and steeper) geometry in Fig. 4 (Plankel and Alexiew 1999).

At that time providing anti-sliding stability in basal and capping systems of landfills by the installation of geogrids started to become a common practice in Germany and first design procedures were developed and applied, see e.g. (Alexiew, 1994).

The new stability analysis for the higher and steeper waste body resulted into significant slope-parallel forces to be taken over by "anti-sliding" geogrids to keeping the entire future waste body in place. The high forces were coupled with stringent requirements in terms of low geogrid strains to limit possible displacements of waste to the right in Fig. 4. The final optimized solution implied geogrids from Aramid (AR): a Fortrac® 1200 A with an ultimate tensile strength (UTS) of 1200 kN/m at less than 3% strain (see project B180 Eisleben above and Fig. 3) on the first slope with a "smooth" liner and a lighter geogrid (but also from AR) Fortrac® 550 A with an UTS = 550 kN/m on the next slopes with a "textured" liner (Fig. 4). The AR was chosen not only because of the high 1tensile strength required but due to the very low short- and long-term strains as well (Alexiew et al, 2000).

Heavy specific anchoring trenches in the berms had to be designed and constructed.

In autumn 1995 a part of the waste adjacent to the first slope was removed and the Fortrac® 1200 A installed. To control the behavior of the system, to verify the design concept and assumptions and to gain comparative information for the next slopes a measurement program was installed. Typical results from one of the strain gauges (also recalculated into a corresponding tensile force F) are shown in Fig. 5; for more details see Plankel and Alexiew (1999).

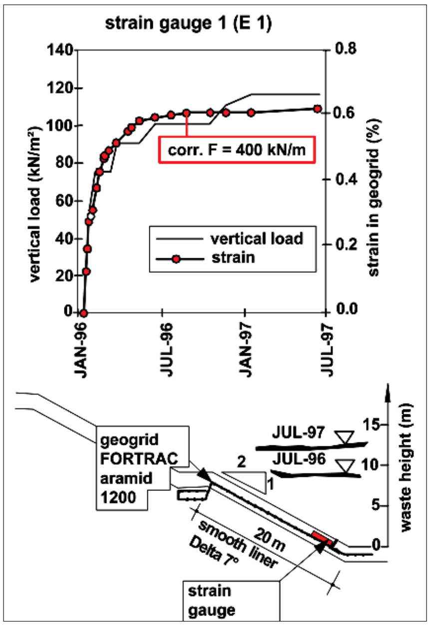


Fig. 5 Filling process and corresponding strains and tensile forces in the geogrids Fortrac® 1200 A at the first slope.

Both strains and tensile forces met the design expectations and the requirements in terms of low strains say displacements.

In autumn 1996 the next (lighter) geogrid Fortrac® 550 A was produced according to the specs and installed on the second slope.

Since summer 1997 the filling process slowed down drastically due to changes in the Austrian regulations. Because of that and of the positive results from the measurements confirming the correctness of assumptions, design procedures and choice of geogrids the measurements were stopped.

Lessons Learned:

Even relatively simple design procedures (based on limit equilibrium and polygonal sliding surfaces) as described e.g. in Alexiew (1994) and Plankel Alexiew and Gartung (1999) are useful and usually sufficient if based on sound and precise assumptions. (Note: today they are implemented with some small modifications in EBGEO 2010).

The appropriate choice of reinforcement (especially of appropriate polymer as raw material) helps not only to guarantee stability but also to control deformations/displacements.

Customized reinforcements result into an optimal solution.

Innovative Aspects:

First use of customized geogrids from AR in landfills.

First production and use of "lighter" AR geogrids based not only on strength but also on low-strain requirements.

First use of geogrids in a landfill to provide not only local stability on slopes but also the global anti-sliding stability of the entire waste body.

PROJECT "KÖRGRABEN AT RATHENOW"

In 1996-1998 the new double-tracked ICE-link (German high-speed trains with up to 300 km/h) Hannover-Berlin had to be built. Near Rathenow the route had to cross a soft soil area of some hundreds of meters known as the "Körgraben" (Graben = valley, buried valley). The DB (Deutsche Bahn = German Rail) as owner looked for a solution guaranteeing not only sufficient bearing capacity but (and mainly) very low total and differential settlements. Especially the latter was of crucial importance not only due to the high train speed but also because the rails had to be installed on an infinite RC-slab (concrete slab track) allowing only for small adjustments of the rails under traffic.

The region is even, thus the system had to be flat and its surface approximately at the level of the terrain. At that time DB had already started with the first projects on georeinforced "piled embankments" with positive experience based also on measurement programs (Brandl et al 1997, Alexiew and Gartung 1999). Thus, the DB was convinced that "piled systems" with geosynthetic reinforcement can work properly. A preliminary design procedure was also available: the so called Older German Method (Alexiew 2002a, 2005, 2008, Alexiew and Vogel 2001) believed to be more realistic than the BS 8006 (BSI 1995), although not codified.

However, in the case of "Körgraben" the "embankment" had to be unusually thin (flat) and finally embedded with its upper surface approximately at the level of the terrain, say not a real embankment but an embedded reinforced "cushion" on piles or columns.

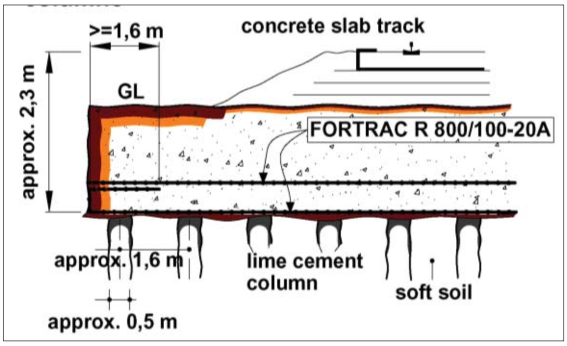


Fig. 6 Typical cross section with 2 x Fortrac® 800 A on cemented stone columns for the ICE route at Körgraben.

After intensive discussions and series of design studies the final optimized solution in 1997 implemented cemented stone columns and geogrid reinforcement from Aramid (AR) (Fig. 6); a positive factor hereby was that the use of geogrids from the same family was foreseen as the ones used for such high-category projects as B180 Eisleben and landfill “Böschistobel” (see above).

Coarse granular well-graded highly compacted fill was used. The uniaxial geogrids Fortrac® 800/100 A with an UTS = 800 kN/m at less than 3% strain were produced for the project (customized) according to the requirements of the design calculations in terms of strength and especially of strictly limited long-term strains for decades under traffic.

The number of geogrid layers was limited to two (1 x across and 1 x along the “embankment”) to reach optimal reinforcement efficiency, because already at that time it was understood that one or two layers of “stronger” reinforcement work better than e.g. three or four layers of “lighter” reinforcement. In the meantime this has been confirmed by further research and is now recommended in EBGEO 2010 (2011).

After execution of the columns a leveling layer of ca. 150 mm of sand was installed, then the bottom (cross) geogrid layer etc (Fig. 7).

After construction in summer 1997 the system was tested by a special heavy dynamic loading device on top simulating for a week by different frequencies and amplitudes the passage of different trains and especially of the ICE-trains equivalent to one month of traffic.

Based on the results of the accompanying measurements the solution was certified by the DB and the Railway authorities. In 1998 the entire ICE-link was handed over for operation.

Until today (after 14 years under traffic) no problems relating to the sensitive “Körgraben” are known or reported. So far the solution proved to be successful.

Fig. 7 Heads of cemented columns and first (bottom) geogrid layer on a leveling sand layer.

Lessons Learned:

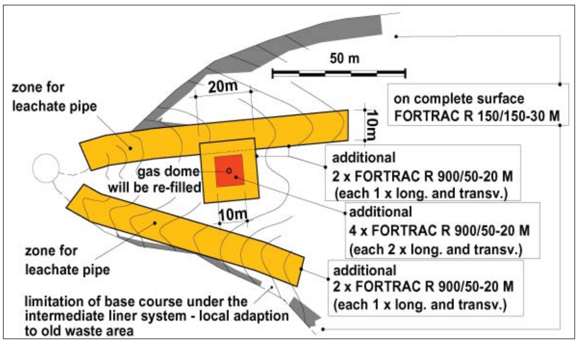
Even “thin” reinforced “embankments” respectively “cushions” on piles/columns can provide not only sufficient stability but also (often more important) very low deformability (total and relative settlements) using high-quality qualified fill and extremely low-strain reinforcements. The philosophy to concentrating a minimal number (maximum two) of strong reinforcement layers nearest to the piles/columns (instead of a “multilayered reinforcement” with e.g. three or four “weaker” layers) seems sound.

Innovative Aspects:

First Aramid (AR) geogrids application worldwide for piled embankments. First AR geogrids application for railroads. First application of any geogrids in systems for high-speed-trains (300 km/h).

PROJECT LANDFILL “EINÖD”

End of the 90ies the municipal landfill Einöd near Stuttgart had to be heightened by more than 30 m to generating additional disposal volume. For this purpose an intermediate (sealing and draining) basal system had to be installed on top of the old fill consisting in accordance to the regulations and to the state-of-the art of mineral and geosynthetic components. The deformations (especially the differential settlements and deflections) of such an intermediate “sandwich” have to be kept below a given limit to ensure an appropriate function of all components (inclusive of e.g. drainage/leachate pipes). The engineering challenge was to create a bearing system ensuring the low deformations



required neutralizing two major problems: the

Fig. 8 Reinforcement scheme for the intermediate basal system of landfill Einöd.

relative inhomogeneity of the old municipal fill resulting into a nonhomogeneuos embedment and the existence of an old gas dome to be closed and bridged. After intensive design studies inclusive of FEM-analyses a solution was chosen consisting of compacted sandy gravels reinforced by geogrids from the same family but with different strengths and positions (Fig. 8).

Note, that beside high tensile forces at low strains an additional requirement was the chemical resistance of the reinforcing geosynthetics due to the specific environment in the landfill.

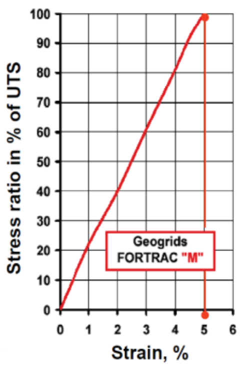


Fig. 9 Typical short-term mechanical behavior of the family of geogrids Fortrac® M from PVA.

Generally high-strength low-strain geogrids from a specific type of Polyvinylalcohol (PVA) were developed and produced to meet all mechanical and chemical requirements. In Fig. 9 their typical stress-strain behavior is depicted demonstrating the mobilization of high tensile forces at low strains reaching the maximum tensile force (100% UTS) at only 5% strain (only Aramids are stiffer, compare the AR-geogrid in Fig. 3 reaching 100% UTS at about 3% strain, but their chemical resistance is in some cases lower; Alexiew et al (2000)).

The Einöd solution implemented a full area

reinforcement from biaxial geogrids Fortrac®

Fig. 10 Installation of the geogrids at the Einöd landfill.

150/150 M and concentrated reinforcements in the most critical zones (pipe embedment, gas dome bridging) from uniaxial geogrids Fortrac® 900 M (the numbers indicate the UTS in kN/m). Figure 10 shows construction stages; note the bridging of the gas dome in the middle, the dozer as a "scale" and the cutting of the heavy geogrids. After construction of the reinforced layers the intermediate (sealing and draining) basal system was installed and the operation of the "new" landfill on top of the "old" one started. Until now (after about 15) years no problems have been identified or reported connected to an inappropriate behavior of the reinforced system.

Lessons Learned:

High-strength high-tensile modulus (tensile stiffness) geogrids can successfully solve problems originating from inhomogeneous embedment, zones prone to differential settlements or potential voids (e.g old domes or shafts).

With the proper choice of raw material (polymer) they can work also in an aggressive environment.

Innovative Aspects:

Production and application for the first time of customized high-strength bi- and uniaxial PVA geogrids with up to 900 kN/m strength.

First application of PVA geogrids in landfills worldwide.

First application of PVA geogrids for bridging a potential sinkhole (the gas shaft) worldwide.

PROJECT "GRÖBERS"

In 2000, a new rail link had to be built connecting Erfurt and Leipzig/Halle in Germany including also a double track for ICE super express trains with 300 km/h (see e.g. ICE "Körgraben" above). The route had to cross in the area of the so called junction Gröbers (with totally 8 tracks, two of them ICE) an old mining area prone to subsidence (sinkholes). The predicted sinkhole diameter was 4.0 m. The entire territory of the junction had to be secured both from the point of view of bearing capacity (ULS) and serviceability (SLS) for the parallel traffic of conventional slower (120 to 160 km/h) but heavy trains and the ICE-trains passing the junction with ca. 260 km/h. Finally the most critical issue was the SLS due to very stringent limitations of deformations over a possible sinkhole: for example the allowed settlement depression: (maximum differential settlement) was max $\Delta s < 3.0$ mm at a rail spacing of 1500 mm. The design life is 60 years.

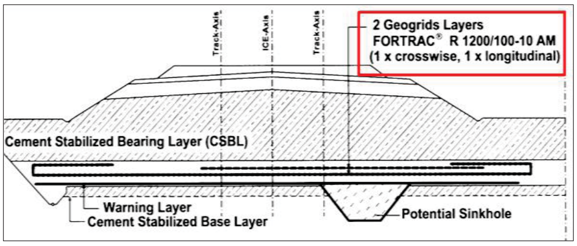


Fig. 11 Simplified scheme of the system for bridging sinkholes at Gröbers.

The philosophy was to keep the deformations below the limit for a month after sinkhole activation under running traffic; in this period the sinkhole has to be re-injected. For identification of the sinkhole a special warning system was developed; it is beyond the scope of this paper. Further details concerning philosophy, requirements, difficulties, warning system, tests etc can be found in Ast et al (2001), Leitner et al (2002) and Alexiew et al (2002b, 2003).

Due to the sophisticated problems the finding of the optimal engineering solution was based on multiple design studies inclusive of FEM-analyses and variation of geometries and materials. The final solution applied is depicted in Fig. 11 in a schematic way.

The system comprises as main bearing components a cement stabilized soil block and two layers of high-strength uniaxial geogrids made in the machine direction (MD, along the roll) from Aramid (AR) and in the cross-machine direction (CMD, across the roll) from PVA with an UTS=1200 kN/m, say the MD was similar to the project B180 Eisleben, see above. The first (bottom) layer of the geogrids Fortrac® 1200/100 AM was installed across the embankment axis, the second one-along.

The short-term tensile stiffness (modulus) is J_{short} = 65000 kN/m and the long-term one is J_{long} = 29000 kN/m at 1.0% to 1.5% strain.

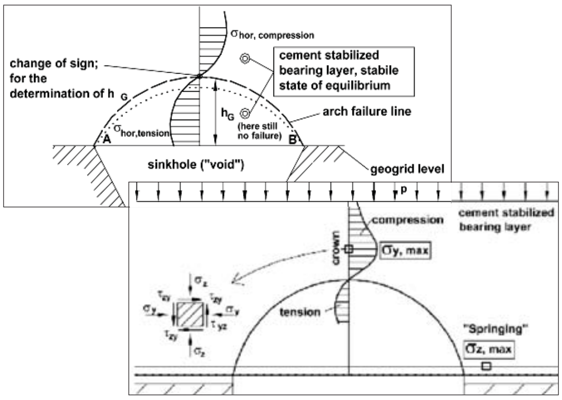


Fig. 12 Examples of alternative simplified procedures developed for "cross-checking" the FEM results.

Despite the FEM-analyses (Alexiew et al 2002b) additional analytical procedures were developed and applied in the sense of a simplified "cross-check" e.g. in regards of the soil-block plastification in combination with the geogrid (Fig. 12).

A 1:1 fragment of the system (Fig. 11) was built and a sinkhole opening under traffic was simulated. The goal was to check the correctness of assumptions, of FEM and analytical design procedures (some of them developed for the project), the constructability of the system and the right choice especially of the reinforcement and its arrangement (Ast et al 2001, Leitner et al 2002, Alexiew et al 2003).

The test confirmed the concept inclusive of the design and final choice of reinforcement.

On the base of the design complete precise installation drawings were made inclusive of specification and numbering of all geogrid layers resp. panels; they were produced and delivered to the site according to these specs with every roll labeled correspondingly.

For the installation of the geogrids a special installation beam was developed and applied allowing some precisely controlled pre-stressing (Ast et al 2001, Leitner et al 2002); it was a continuation of the installation philosophy at B180 Eisleben in 1993 (see above) at a qualitatively higher level (Fig. 13).

In some moments before execution started some doubts arose if the entire sophisticated system as described is worth, if the risk of sinkholes is real and even if they will occur at all. All doubts disappeared when at the same beginning of construction sinkholes started to open (Fig. 14).

In 2002, the junction Gröbers was completed and handed over for operation.

Fig. 13 Installation of the geogrids at Gröbers.

Fig. 14 A sinkhole opening during execution.

Lessons Learned:

Creative and competent multiple engineering with a touch of conservatism can result in successful new systems never built before; their behavior can be predicted quite precise.

For sophisticated systems with a high degree of novelty it is very useful to combine numerical and analytical (even simplified) procedures; they can be "invented" say developed based on general geotechnical postulates if required.

Customized georeinforcement is a good way to both safe and optimal solutions.

For novel geotechnical systems for high category structures a 1:1 test should be recommended.

In areas known to be prone to subsidence (karst, mining etc) the risk should never be underestimated; appropriate technical solutions to secure infrastructure should be implemented.

Constructability and quality assurance have to be kept in mind already in the design stage inclusive of installation drawings.

Stabilized soils and appropriate geogrids can be successfully combined.

Innovative Aspects:

First system with Aramid (AR) geogrid reinforcement bridging sinkholes under high-speed trains.

First geogrid reinforcement combining AR (MD, main direction) and PVA (CD, cross direction).

First system for bridging sinkholes combining stabilized local soils and geogrids.

First system including a full area warning/controlling biaxial geotextile-based layer.

FINAL REMARKS

Due to brevity only a limited selection of case studies is presented herein. A significant number of other projects in the last 15 to 20 years could also meet the criteria set by the authors: pioneering solutions, demanding structures being "sensitive" and problematic either "a priori" or due to their high category of responsibility, high degree of novelty in the sense of application of geosynthetic reinforcements and the development and introduction of often customized innovative materials (herein from Aramids (AR) and Polyvinylalcohol (PVA)). May be there will be an occasion to publish a similar chronological overview of other projects in future.

Summarizing: the experience until now is encouraging. All the projects are since many years in operation and thus approved by practice.

ACKNOWLEDGEMENTS

Many esteemed colleagues participated in the projects described representing owners, investors, consultants, supervisors, authorities and - last but not least - the company of the authors: the list is long. Only some of them appear as authors in the References below. There engineering competence, engagement, acceptance of new solutions and often enthusiasm are highly appreciated.

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