Multi-layer Geosynthetic Reinforced Embankment Over Potential Sinkholes for a Rapid Rail Link in South Africa

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ABSTRACT

The 80-kilometre twin-track of the Gauteng Rapid Rail Link in South Africa is being constructed to connect the principal business hubs of Johannesburg, Sandton, Centurion, Pretoria and O.R. Tambo International Airport. From Centurion to the southern outskirts of Pretoria the route crosses terrain where sinkholes of up to 50-metre diameter have occurred without warning because of the collapse of solution cavities in the underlying Dolomite rock.

For a distance of about five kilometres, where the potential sinkhole diameter exceeds five metres, the twin railtracks will be cradled in a 10 m wide by 1.5 m deep, post-tensioned concrete, U-shaped ground-beam. The U-beam, designed to prevent derailment if a sinkhole should occur at a random location beneath the railway, traverses two embankments with a total length of one kilometre and a maximum height of thirteen metres. To maintain the required subgrade support to the U-beam the embankments have been reinforced with composite geotextiles distributed uniformly through the depth of the fill.

This method was found preferable to piling, cement stabilisation or basal reinforcement for reasons that included cost, speed of construction and simplicity of quality control procedures.

1. INTRODUCTION

The main corridor of the Gautrain Rapid Rail Link, now under construction, runs northwards from Johannesburg through Sandton and Centurion to Pretoria, with an eastward connection to the O.R. Tambo International Airport. For about 16 km from Centurion to the southern outskirts of Pretoria, the route is underlain by Dolomite riddled with large solution cavities. The cavities are partly or wholly filled with chert rubble and erosion-prone silt called WAD (Weathered Altered Dolomite) that makes detection by borehole or geophysical investigation uncertain and inhibits improvement by grouting. Sinkholes of up to 50 m diameter have occurred without warning when such cavities have collapsed.

Sinkhole size and frequency is related to localised geological and ground-water conditions (Buttrick & van Schalkwyk, 1998) and after intensive investigation of the rail corridor it was decided that, in conjunction with settlement monitoring and measures to control water infiltration, the track support system would be designed to accommodate the sudden occurrence of a randomly located sinkhole with a diameter of 15 m.

Except where carried on a viaduct with deep-piled foundations, the twin-tracks are cradled in a 10 m wide by 1,5 m deep, post-tensioned, concrete, U-shaped ground-beam. Dynamic Consolidation was used extensively to improve and control the sub-grade support to the U-beam at existing ground level and in cut.

Embankment fills to a total length of one kilometre and a maximum height of 13 m presented a special challenge. Basal reinforcement (BS8006 or SANS 207:2006 clause 11.4) was found to be impractical for spanning sinkholes of more than about 5 m diameter so it was necessary to strengthen the fill itself. Quality of available fill materials varied widely and it was important, in order to limit cost and environmental impact of the earthworks, that haul distances and re-handling be minimised. In these circumstances it was found that strengthening with geogrid reinforcement would be less costly, quicker to construct and more reliable than cement stabilisation.

The solution adopted was to embed, at 500 mm vertical intervals through the depth of the fill, horizontal sheets of the composite polyester reinforcing geotextile RockGrid PC.

2. DESIGN OPTIONS

Basal reinforcement has been used to safeguard against the development of sinkholes beneath embankments supporting motorways and rail systems in Germany (Leitner et al, 2002), France (Blivet et al, 2000) and other countries (BS 8006).

Figure 1 illustrates how the basal reinforcement layer is designed to prevent collapse of embankment material into a sinkhole. It also shows the subsidence that occurs in the embankment over the sinkhole due to the strain required to mobilise the tensile strength of the reinforcement.

The diameter D_s of the subsidence bowl, a function of the strength and stiffness of the fill material, is greater than the diameter of the void in the ground beneath the fill.

To span a 15 m diameter sinkhole it was found that the strength and stiffness requirements for the basal reinforcement were inordinately expensive to achieve. Furthermore, even if the basal reinforcement was strong enough not to rupture, the surface depression d_s would be greater than the permitted vertical deflection of the railtrack and hence the U-beam would still be necessary.

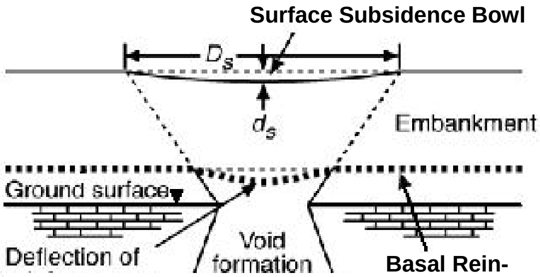

Figure 1: Basal reinforcement – adapted from Fig. 73 of SANS 207:2006

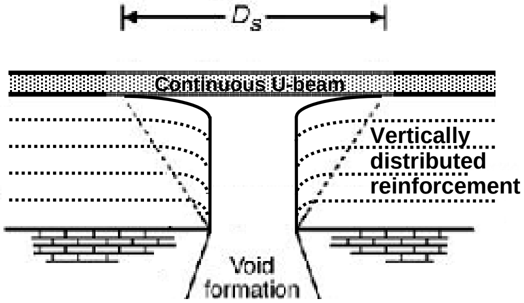

Figure 2: Vertically distributed earth reinforcement with U-beam

Given that the U-beam is necessary on top of the embankment, the primary design requirement is not to prevent propagation of the sinkhole upward into the embankment as in the case of basal reinforcement, but to limit the diameter and the vertical deflection of the subsidence bowl by increasing the stiffness and tensile (cohesive) strength of the embankment itself. This could be done either by cement stabilisation of the fill material or by distributing tensile reinforcement through the height of the embankment, as shown in Figure 2.

3. DISTRIBUTED GEOSYNTHETIC REINFORCEMENT OR CEMENT STABILISATION?

Preliminary design assessment indicated that tensile reinforcement would be more cost effective than cement stabilisation, and the geosynthetic option also presented clear technical advantages.

3.1 Material Handling

With both methods of ground improvement, the fill would be placed in layers of similar thickness and with similar compaction requirements, but to mix in cement and compact the fill within the hydration window introduced more onerous time constraints than rolling out layers of geosynthetic. Furthermore, the cement itself would be heavier and more difficult to transport, store and handle than the geosynthetic and would introduce additional dust-control requirements.

3.2 Variability of the Fill Materials

To reduce the cost and environmental impact of earthworks, the mass-haul strategy was to produce a small surplus of material. The objective was to ensure that as much as possible of the material excavated from cut would be moved directly to an adjacent fill with minimal stockpiling or re-handling. The ground improvement method therefore had to be suitable for use on a wide range of soil types, excluding only excessively wet or highly plastic materials, which were not expected to be encountered in significant quantities on this project.

Some selection and differentiation would be done to avoid the unnecessary expense of treating all soils to suit the worst possible materials, but it was important to use simple selection criteria to avoid time delays and mistakes.

Geosynthetics had a distinct advantage in this regard as there was no technical or environmental disadvantage to using a higher than necessary level of reinforcement, whereas too high a cement content would make the fill brittle and more likely to crack from shrinkage of hydration.

4. FIELD DEMONSTRATION

The concept of geosynthetic reinforcement designed to rupture over a large diameter sinkhole while maintaining the tensile strength of the adjacent fill material was sufficiently novel as to warrant a field demonstration of the process. A fully instrumented field trial would have greatly enhanced the subsequent design process but was not achievable within the time available and subject to safety controls devised for a large construction project, rather than a closely monitored field experiment.

The model embankment needed to be large enough to avoid controversy over scale-related issues, and to clearly demonstrate the method of construction and mode of failure to the project managers. This was achieved by building a five metre high, nine metre square, retained enclosure filled with sand of which the lower three metres was fabric reinforced, and then create a void below the reinforced material. The result was effective and convincing but yielded little quantitative information.

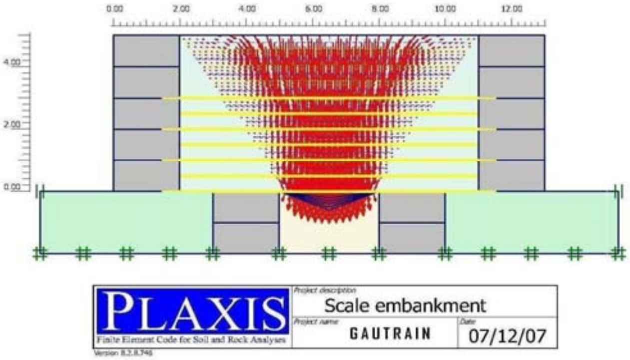

Figure 3: Section through 9 m square 5 m high embankment undermined by washing out a 3 m wide trench

The model embankment was constructed in ten 500 mm thick layers of un-compacted sand. The bottom seven layers were each placed on a sheet of needle-punched non-woven polyester, bidim A0, the weakest commercially available geotextile. The strength of 6 kN per metre (at an elongation of between 40 % and 60 %) was about 5 % of that of the composite geogrid that was subsequently used in the actual rail embankment.

Figure 4: Creating the “sinkhole”

Figure 5: Undermined from below, the sides of the resultant trench were close to vertical

5. DESIGN

A series of elasto-plastic FEM analyses were done to determine the optimal strength, stiffness and spacing of distributed tensile reinforcing in the embankment over a large void. Strains and vertical stiffness profiles adjacent to the void were passed to the structural engineer who designed the U-beam supporting the railtrack to span the void within the specified deflection criteria.

5.1 Design Assumptions

For the purpose of analysis it was assumed that:

- The strength and stiffness of the geogrid buried in the soil (no exposure to ultraviolet light) will not deteriorate with age.
- The fill is not unduly aggressive (5 < pH < 9), no significant deleterious chemical content.
- Age reduction factors for creep under load were ignored because the tensile load in the geogrid is negligible (in relation to design strength) until a sinkhole occurs.
- The collapse of a sinkhole large enough to cause settlement approaching the design tolerance would be detected by the settlement monitoring system and would be repaired (by grouting, slab jacking or other remediation) within a few days of the occurrence, so creep was ignored.
- The layout pattern of successive layers of reinforcement within the embankment fill would be staggered to ensure that the laps in any one layer of geosynthetic did not coincide with laps in other layers above or below.

5.2 Properties of Embankment Fill

Analyses were conducted for two qualities of fill material: a "good" fill and a "moderate" fill. It was assumed that these fill materials, compacted in the embankment, would meet the following minimum criteria:

Table 1: PROPERTIES OF EMBANKMENT FILL

Material Quality	**Good Fill**	**Moderate Fill**	
		Non-plastic	Plastic
TRH14 Class	G6	G8	G8
CBR	25	10	10
ϕ' (degrees)	36	31	20
Cohesion (kPa)	5	1	10
Young's mod.(MPa)	40	20	20

5.3 Method of Analysis

The analyses were conducted using Plaxis Version 8.2. The Mohr-Coulomb failure criterion was used for all fill materials.

The reinforcing was modelled as linear elastic membrane elements with the short-term stress-strain properties of typical commercially available knitted polyester composite geotextiles. The vertical spacing between membranes was 500 mm for all analyses. Smaller spacing created problems with the configuration of the finite element mesh. Changes in vertical spacing were simulated by pro-rata changes to the stiffness of the membrane elements.

Shear stress at interfaces between geosynthetic and soil was limited to 2/3 (or 67 %) of the shear strength of the soil. Maximum tension in the membranes was limited to thirty percent of the ultimate strength, and creep was not considered.

The analyses used for the design were done under "plane strain" conditions. In a comparative axi-symmetric analysis, of a 15 m diameter "sinkhole" there was an insignificant reduction in deflections. Modelling the propagation of a sinkhole upwards through an embankment with the finite element method was found to be possible, but extremely time consuming. To model large plastic strains requires thousands of iterations to converge to a stable configuration at each loading step, which takes several hours, or even days, to compute. As yield of a Mohr-Coulomb soil model is independent of stress path, if the final configuration of the model is known as in this case from simulation of the collapse, it is not necessary to progressively model the stages of the collapse.

The effect of the sinkhole on different heights of embankment was therefore modelled by successively removing from the top down a vertical stack of elements, more closely analogous to the excavation (in a suitably reinforced soil) of a vertical-sided trench.

6. CONSTRUCTION

6.1 Ease of Construction

No specialised labour or plant was required to install the composite reinforcing geotextile, which contributed to the time saving. The geosynthetic was rolled out by hand in overlapping rolls to the width of the embankment before placing the backfill and compacting as normal. The biaxial composite geotextile provided uniform strength in all directions and could be oriented as site conditions required, adding to the convenience of the system.

Figure 6: Laying composite geogrid

6.2 Quality Assurance

The geosynthetic manufacturing facilities were ISO 9001 accredited with certificates of conformance available for every roll of product produced. The composite geotextiles were tested at the SANAS accredited Geosynthetic Laboratory according to international standards. With the onsite preparation of cement-stabilised fill, there is always room for error even with technologically advanced plant.
The use of reinforcing geotextiles provided better quality assurance and measurable performance criteria.

6.3 Composite Geotextile Reinforcement

The geosynthetic used in the fill embankment is a composite geotextile that combines the desirable reinforcement characteristics of a high-tensile modulus, low-creep, polyester geogrid in conjunction with the favourable mechanical and hydraulic properties of a nonwoven geotextile. The nonwoven component protects the high-tensile component against mechanical damage during placement and compaction and provides drainage capacity within its plane, i.e. transmissivity, enabling it to reduce pore pressure build-up in the reinforced soil, thereby improving the internal shear resistance and overall stability of the structure.

Two strengths of biaxial composite geotextile reinforcement were specified and installed, namely 100 x 100 and 200 x 200 kN/m, respectively.

Figure 7: Aerial view of multi-layer geosynthetic reinforced embankment

7. CONCLUSIONS

The use of geosynthetics is fast becoming common practice in the civil engineering industry as an alternative to conventional methods of design and construction. This is evidenced by the adoption on this high profile project of custom-designed geosynthetic reinforced embankments over potential sinkholes. The inclusion of high-strength, low-strain, composite geotextile reinforcement vertically distributed through the fill greatly enhanced the sub-grade support to the U-beam that carries the Rapid Rail tracks.

The contractor found this system to be a good method of construction. Although the cost advantage of the geosynthetic over cement stabilisation did not prove to be as significant as originally estimated, the technical advantages of the multi-layer geosynthetic reinforcing system were substantial and allowed the contractor a considerable time saving on a very tight construction programme.

ACKNOWLEDGEMENTS

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