

# Multi-layer geosynthetic-reinforced embankment over potential sinkholes for a Rapid Rail Link in South Africa

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**Keywords:** geosynthetic, geogrid, reinforce, composite geotextile, stabilize, embankment, earth, soil, fill, stiffness, sinkhole, void, subsidence, multi-layer, basal, settlement control, unstable ground,

**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 sudden 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 rail-tracks will be cradled in a 10m wide by 1,5m deep post-tensioned concrete U-shaped ground-beam. The U-beam, which has been designed to prevent derailment if a sinkhole should occur without warning at a random location beneath the railway, traverses two embankments with a total length of one kilometre and maximum height of thirteen metres. To maintain the required subgrade support to the U-beam the embankments have been reinforced with geogrids distributed uniformly through the depth of the fill.

This method was found preferable to piling, cement stabilization 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 16km 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 50m 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 15m.

Except where carried on a viaduct with deep-piled foundations the twin-tracks are cradled in a 10m wide by 1,5m 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.

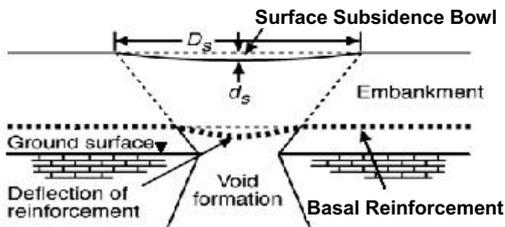
Embankment fills to a total length of one kilometre and a maximum height of 13m presented a special challenge. Basal reinforcement (BS8006 or SANS 207:2006 clause 11.4) was found to be impractical for spanning sinkholes of more than about 5m diameter so it was necessary to strengthen the fill itself. 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 include at 500mm vertical intervals through the depth of the fill horizontally embedded high strength composite geotextiles of the type 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.



**Figure 1:** Basal reinforcement - adapted from Fig. 73 of South African National Standard SANS 207:2006

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 15m 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.

Given that the U-beam was required even on top of the embankment, the primary design requirement was 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.

## 3 CEMENT STABILISATION OR DISTRIBUTED REINFORCEMENT?

Preliminary designs indicated that cement stabilisation of the fill would be more expensive, but geosynthetic reinforcement also had clear technical advantages.

### 3.1 Material handling

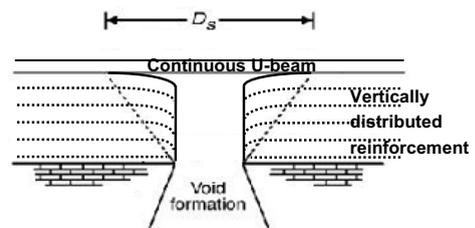
With both methods of ground improvement the fill would be placed in layers of similar thickness and with similar compaction requirements, but to mix in cement and compact the fill within the hydration window introduced more onerous time constraints than rolling out layers of fabric. Furthermore, the cement itself would be heavier and more difficult to transport, store and handle than the fabric 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 designed 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 unlikely to be encountered in significant quantities on this project.

There was financial pressure for some selection and differentiation, it would have been expensive to stabilise all soils to suit the worst possible materials, but it was important to use simple 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



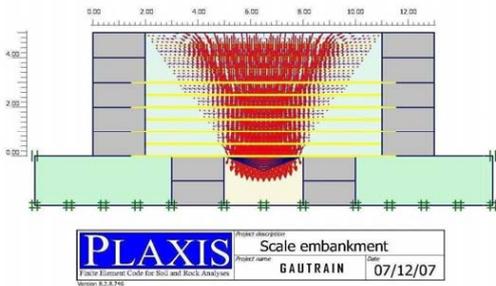
**Figure 2:** Distributed earth reinforcement with U-beam

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, rate-controlled, field trial would have greatly enhanced the subsequent design process. Within the time available and subject to safety controls devised to suit a large construction project, rather than a closely monitored field experiment, the demonstration yielded little quantitative information.

The over-arching requirement was that the field trial be large enough to avoid controversy over scale-related issues and to demonstrate clearly the method of construction and the mode of failure to project managers with limited technical background knowledge. The compromise solution was to build a five metre high nine metre square retained enclosure filled with sand, of which the lower three metres was geosynthetic reinforced, and then create a void below the reinforced material.



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



**Figure 4:** Creating the "sinkhole"

The model embankment was constructed in ten 500mm thick layers of un-compacted sand. The bottom six layers were each placed on a sheet of needle-punched nonwoven polyester, Bidim A0, the lightest and weakest commercially available geotextile. The short-term ultimate tensile strength of 6 kN per metre (at an elongation of between 40% and 60%) was about 5% of that of the composite geogrid to be used in the rail embankment.



**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 optimise the requirements for the 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 rail-track to span the void within the specified deflection criteria.

### 5.1 Design Assumptions

- The strength and stiffness of the geogrid buried in the soil (no exposure to ultra-violet light) will not deteriorate with age.
- The fill is not unduly aggressive ( $5 < \text{pH} < 9$ ), with no significant deleterious chemical content.
- Ignore age reduction factors for creep under load because tensile load is negligible (in relation to design strength) until sinkhole occurs.

It was also assumed that a sinkhole collapse 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.

The layout pattern of successive layers of reinforcement within the embankment fill would be staggered so that the laps in any layer of geosynthetic would

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:

Material Quality:	Good Fill	Moderate Fill
TRH14 Class	G6	G8
CBR	25	10
$\phi'$ (degrees)	36	31
Cohesion (kPa)	5	1
Young’s mod.(MPa)	40	20

### 5.3 Method of Analysis

The analysis was conducted using Plaxis Version 8.2.

The Mohr-Coulomb failure criterion was used for all fill materials.

The reinforcing was simulated 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 500mm 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.

Creep was not considered.

The analyses used for the design were done under “plane strain” conditions. In a comparative axisymmetric analysis, of a 15m 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. A numerical model experiencing large plastic strains requires thousands of iterations to converge to a stable configuration at each loading step. Each analysis takes several hours, or even days, to compute.

Yield of a Mohr-Coulomb soil model is independent of stress path and, if the final configuration of the model is known as in this case from simulation of the collapse with a trial embankment, 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 succes-

sively 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 specialized labour or plant was required to install the geosynthetic reinforcing, 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 used provided uniform strength in both directions and could be orientated as site conditions allowed, adding to the convenience of the system.



**Figure 6:** Laying composite geotextile

### 6.2 Quality assurance

The geosynthetic manufacturing facilities are 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 stabilized fill, there is always room for error even with technologically advanced machines. Therefore, the use of these geosynthetics provided far greater quality assurance and measurable performance criteria.

### 6.3 Composite Geosynthetic Reinforcement

The geosynthetic used in the fill embankment is a high strength, composite, reinforcing geotextile that offers the 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 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 as well as protecting the reinforcing elements from mechanical damage during backfill placement and compaction.

Two strengths of biaxial geosynthetic were specified namely, 100 x 100 and 200 x 200 kN/m, respectively.



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

## 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.

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Acknowledgements: Bombela Civils Joint Venture Pty Ltd