The paper was published in the proceedings of the 17th African Regional Conference on Soil Mechanics and Geotechnical Engineering and was edited by Prof. Sw Jacobsz. The conference was held in Cape Town, South Africa, on October 07-09 2019.

The use of ductile steel reinforcement for a soil mattress

A.C.S. Smith
Reinforced Earth (Pty) Ltd, Johannesburg, South Africa

K. Truong
Reinforced Earth Company Ltd, Arlington, USA

ABSTRACT: A 350 m by 400 m industrial site was underlain by dolomites. An assessment of the Site indicated that 2.5m and 3.5m diameter sinkholes could form at the surface and should be considered for design purposes. The industrial structures would be founded on reinforced concrete surface rafts. Deflections beneath the reinforced concrete rafts should be minimal in order not to exceed the allowable bending moments in the rafts. Deflections in areas between the rafts should not compromise the integrity of the roads and other surface installations. The use of a soil mattress reinforced with ductile steel reinforcements was analysed using 3D FLAC analysis. A paper by Professor Geoff Blight (references) shows that the use of ductile steel reinforcement provides an inherently safe structure since the reinforcement will ultimately act as a catenary net and prevent catastrophic failures occurring. In order to test the catenary theory, the analysis was run with the formation of a 10 m diameter sinkhole. An analysis for different loadings, sinkhole diameters with and without reinforced concrete rafts, was undertaken. Illustrations of the FLAC analyses are shown, and a summary of the results tabled. The conclusion drawn is that a ductile steel reinforced soil mattress could provide an economical solution to develop land over dolomites for both industrial and residential purposes.

1 INTRODUCTION

French engineer Henri Vidal invented Reinforced Earth in the 1960s. The technology has since been used throughout the world for a wide range of transport, mining, industrial, military, commercial and water related applications. Vidal postulated many applications for the new material one of which was for rafts.

An opportunity arose in South Africa to provide a raft structure as a foundation for an industrial site. A design was prepared, but the project was shelved. Although not constructed it is felt that the best R&D is stimulated by a real project and that the proposed design could provide an economical solution to develop land on which relatively small diameter sinkholes could develop.

2 THE SITE

The area of the site was equivalent to about 18 rugby fields (10 hectares). Various structures on the site would be founded on reinforced concrete surface rafts. The areas between the surface rafts comprise roads and do not have any surface raft.

The geology comprises a transported layer, underlain by intrusive syenite underlain by dolomite and chert residuum and in turn by hard rock dolomite.

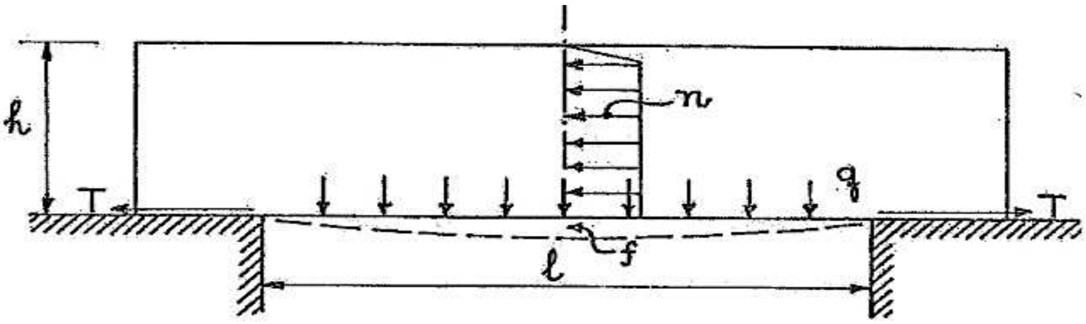
The geotechnical engineers recommended that the transported material be removed and replaced with a soil mattress which would form a platform, seal the area from ingress of water and bridge potential sinkholes. The site was divided into 2 zones- one with a risk of 2 m diameter and one with a risk of 3.5 m diameter sinkholes.

The material above the dolomite is intrusive syenite which ranges in depth between 10 m and 25 m. Water could leach away material at the interface of the syenite and the dolomite which could lead to a myriad network of eroded columns leading upwards to the soil mattress foundation level.

It is envisaged that the sinkholes could develop at the foundation level with say, 60 degree sides funnelling down to a “throat” 0.5 m wide and 6 m deep.

In order to gain approval of the design from the local Council of Geosciences, it was necessary to show that development of larger sinkholes would not be catastrophic or life threatening.

The analysis was undertaken for the development of a 10 m diameter sinkhole beneath the mattress.



n = compressive stress in unreinforced section
q = unit load on membrane = $K_a . n$.
l = span or diameter of slab
f = deflection at midpoint of slab

T = Tensile force at edge of membrane
h = depth of beam or slab
A_s = area of reinforcement

$$T = A_s . E. \frac{\Delta l}{l} \quad \text{...... Equation 1}$$

$$f = \frac{q . l^2}{16T} \quad \text{............ Equation 2}$$

Figure 1. Assumption of raft behaviour (Source: SAICE Geotechnical: Seminar on Ground Improvement 2001)

3 THE DESIGN

3.1 *Assumption*

Basic assumption of soil mattress is that the mattress would behave as a slab with tension taken by the reinforcing strips at the bottom of the mattress and compression by the soil above the strips - shown as a beam in 2 dimensions in Figure 1.

The soil mattress is designed to act as a slab. The tension element being the reinforcing strips and the compressive element being the soil above it and, if present, reinforced concrete surface rafts.

Since it is the ingress of water that triggers the sinkholes, the mattress was to be designed to prevent ingress of surface water into it.

3.2 *Design criteria*

Should a 2 m or 3.5 m diameter hole occur then:
- deflections beneath the reinforced concrete rafts should be minimal.
- deflections outside of the rafts should not cause disruption to the plant.
- bending moments in the rafts should be checked against the design bending moments.
- the unexpected development of a 10m diameter sinkhole should not endanger lives.

Five cross sections were analysed using FLAC 3D:
- Run 1: 2m diameter with raft
- Run 3: 2m diameter without raft
- Run 4: 3.5m diameter with raft
- Run 6: 3.5m diameter without raft
    - 6a 3.5m mattress
    - 6b 250kPa stabilised layer
- Run for 10 m diameter sinkhole without surface raft.

3.3 *Geometry*

a. The mattress thickness to be 2000 mm thick from the top of the foundation to the underside of the reinforced concrete raft or finished ground level as shown in Figures 4, 5, 6, 7 and 10. A run with mattress thickness 3.5 m was undertaken on one run - Run 6a.
b. 150 mm of selected backfill beneath and above the steel strips.
c. The cement stabilised layer was 300 mm thick and had a strength of 125 kPa.

3.4 *FLAC adjustments*

- Geotextile needs to be surrounded by backfill on both sides. The run then does not include a geotextile placed on foundation level.
- In order to prevent fill falling between the reinforcing strips, the reinforcing strips were simulated as a sheet of steel preventing fill from falling through them.

4 MATERIAL PROPERTIES USED IN FLAC ANALYSIS

4.1 *RC Raft*

Bulk Mod 5.56e9 Pa; Shear Mod 4.176e9 Pa; density 25kN/m^3; Ø = 26°; cohesion = 250 kPa

4.2 *Backfill lower and upper mattress*

Dilation angle = 4°; Density = 19.5 kN/m^3; Ø = 32° cohesion = 2.5 kPa;
Young's modulus = 80 MPa; Poisson's ratio 0.275

4.3 *Stabilised layer*

Bulk Mod 5.56e9 Pa; Shear Mod 4.176e9 Pa; density 23kN/m^3; Ø = 26°; cohesion = 125 kPa.

4.4 *Residual Syenite*

Density = 16.5 kN/m^3; Ø = 27.5°; cohesion = 5 kPa; Young's modulus 50 MPa; Poisson's ratio = 0.33.

4.5 *Reinforcing Strips*

Hot rolled, ribbed, medium tensile steel with 25% elongation before rupture. Ultimate load in strips 119 kN, yield at 80kN. Allowing for sacrificial thickness for 100 years ultimate load is 83 kN and yield load is 56kN.

The strips are placed on one level in two directions at spacing shown in Figure 2.

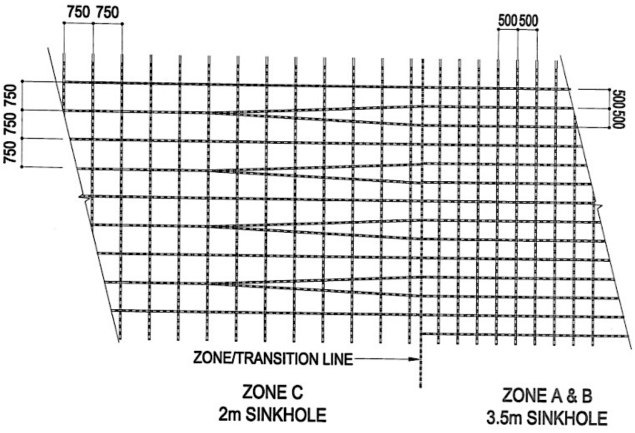


Figure 2. Plan on reinforcing strips

The reinforcing strips are padded and the connection is designed to be stronger than the strips ensuring full elongation in the strip (Fig. 3).

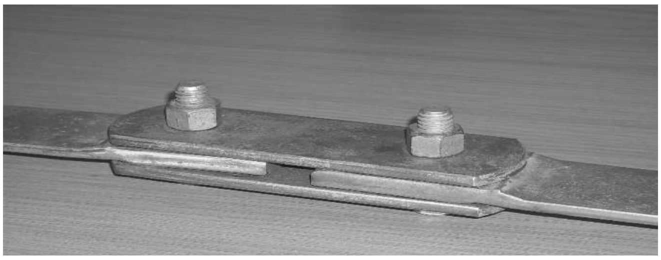


Figure 3. Connection 45 mm x 5 mm ribbed and padded reinforcing strips.

Durability - strips and connections are hot dip galvanised with sacrificial thickness for 100-year service life.

The FLAC analysis proved to be a lengthy process. For Run No 1 bringing the foundation, fill and raft to equilibrium took 33 hours and then the addition of the uniform tank load of 330 kPa took a further 6 hours to come to equilibrium.

5 THE RUNS AND RESULTS – 2.0M AND 3.5M DIAMETER SINKHOLES

5.1 *Run 1-2.0 m diameter sinkhole; 450 mm raft with 330 kPa loading (Figs 4, 6, 8)*

- Max strip tension - 15.46 kN
- Deflection at bottom of slab 4.5 mm
- Deflection at strip level 146 mm
- Maximum bending moments in slab - negative -200 kN-m/m, positive 360 kN-m/m

5.2 *Run 3-2.0 m diameter sinkhole; 20 kPa loading (Figs 5, 7)*

- Max strip tension - 19.29 kN
- Deflection at top of fill - 125 mm
- Deflection at strip level - 217 mm
- Compressive stress over most of upper mattress

5.3 *Run 4-3.5 m diameter sinkhole; 450 mm raft with 350 kPa loading*

- Max strip tension - 47.10 kN
- Deflection at bottom of slab - 23.3 mm
- Deflection at strip level - 550 mm
- BM in slab - negative -250 kN-m/m (-35 kN-m/m
- over small area; positive 200 kN-m/m) (high point 482 kN/m-m at centre local high point)

5.4 *Run 6-3.5 m diameter sinkhole; 20 kPa loading; 300 mm thick stabilised layer-125 kPa (Fig. 9)*

- Max strip tension - 57.88 kN
- Deflection at top of fill - 400 mm
- Deflection at strip level - 667 mm

5.5 *Run 6a - 3.5 m diameter sinkhole; 20 kPa loading; 3.5 m mattress; 300 mm stabilised layer -125 kPa*

- Max strip tension - 65.16 kN
- Deflection at top of fill - 400 mm
- Deflection at strip level - 657 mm

5.6 *Run 6b - 3.5 m diameter sinkhole; 20 kPa loading; 3.5 m mattress; stabilised layer 250 kPa*

- Max strip tension - 65.04 kN
- Deflection at top fill - 400 mm
- Deflection at strip level - 657 mm

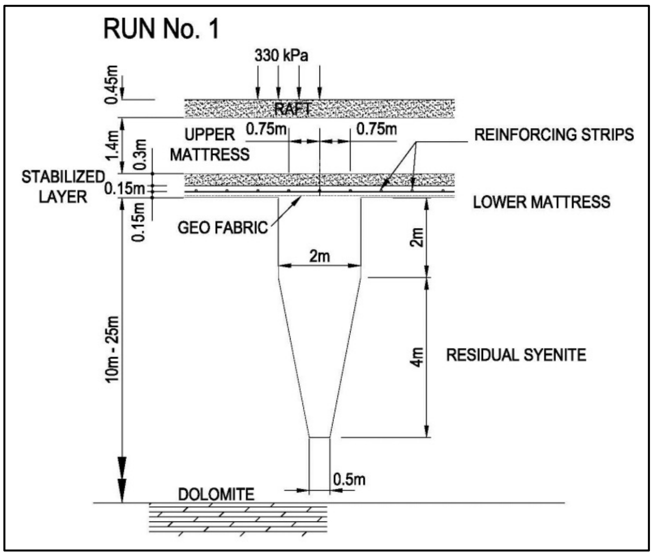


Figure 4. Cross section 2 m diameter sinkhole.

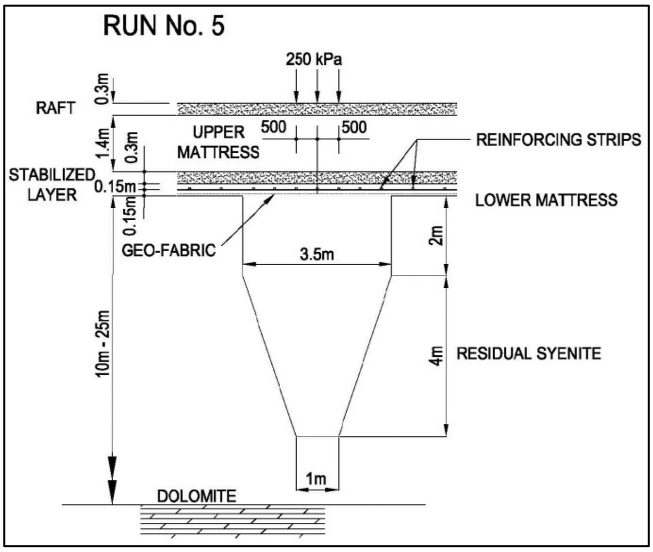


Figure 5. Cross section 3.5 m diameter sinkhole.

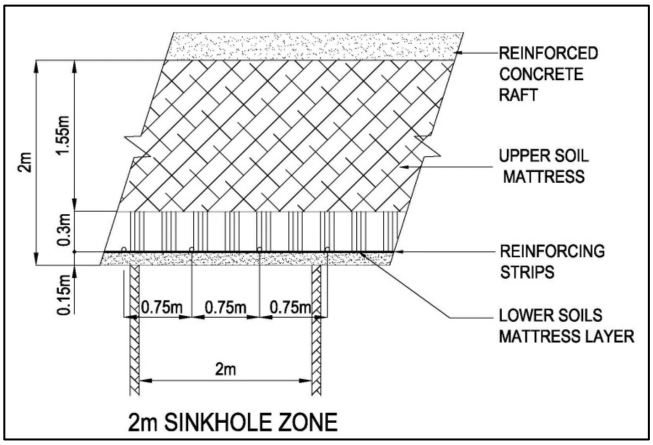


Figure 6. Run No. 1: Cross section used for FLAC analysis.

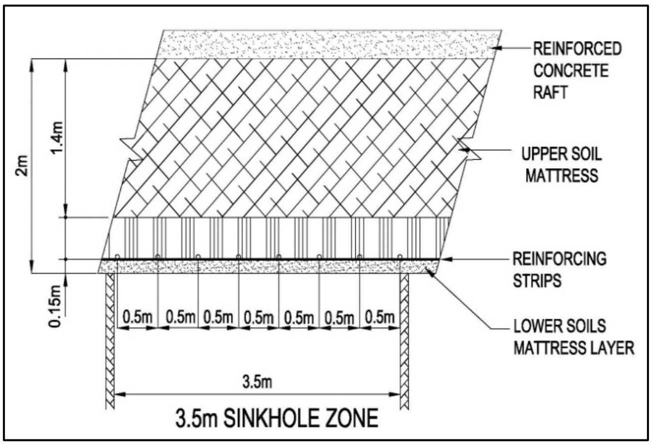
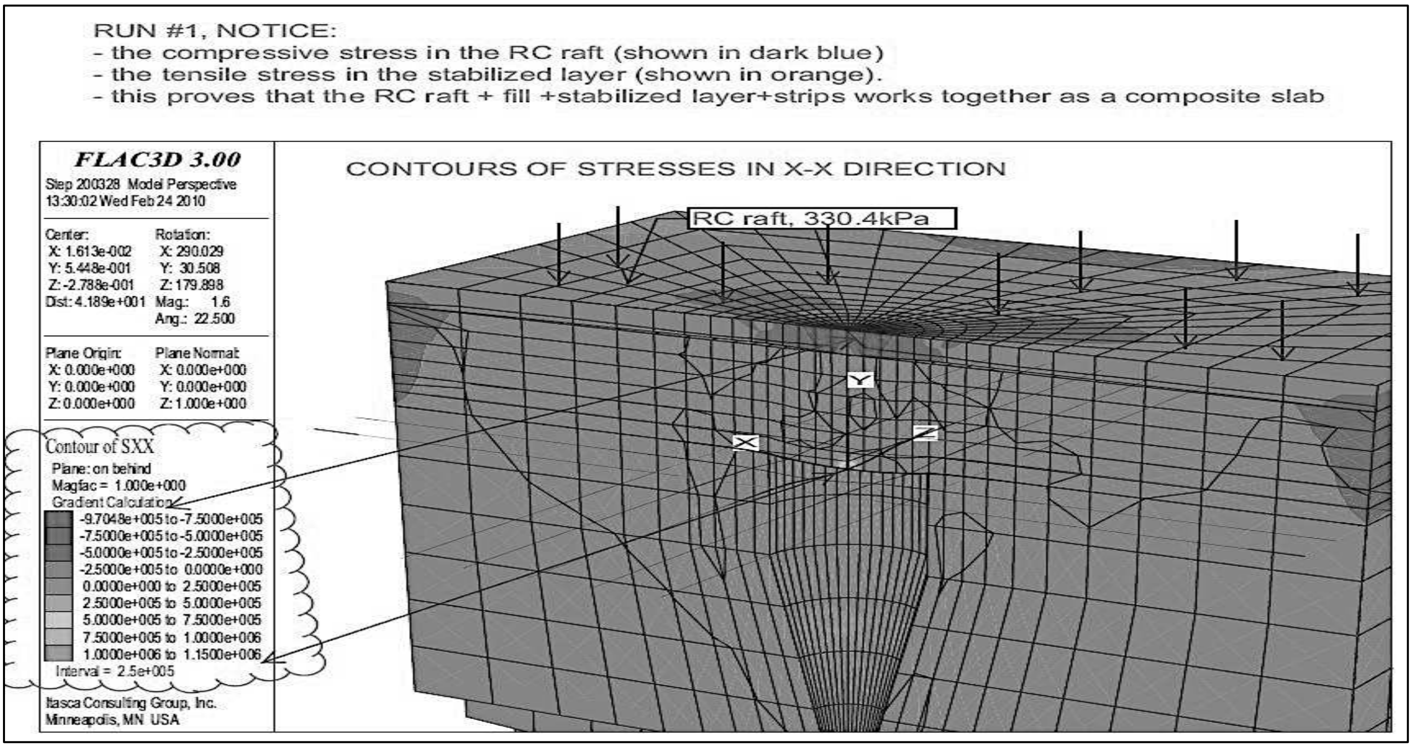


Figure 7. Run No. 5: Cross section used for FLAC analysis.



RUN #1, NOTICE:
- the compressive stress in the RC raft (shown in dark blue)
- the tensile stress in the stabilized layer (shown in orange).
- this proves that the RC raft + fill +stabilized layer+strips works together as a composite slab

Figure 8. Run 1 - 2.0 m diameter with raft - contours of stresses in X - X direction.

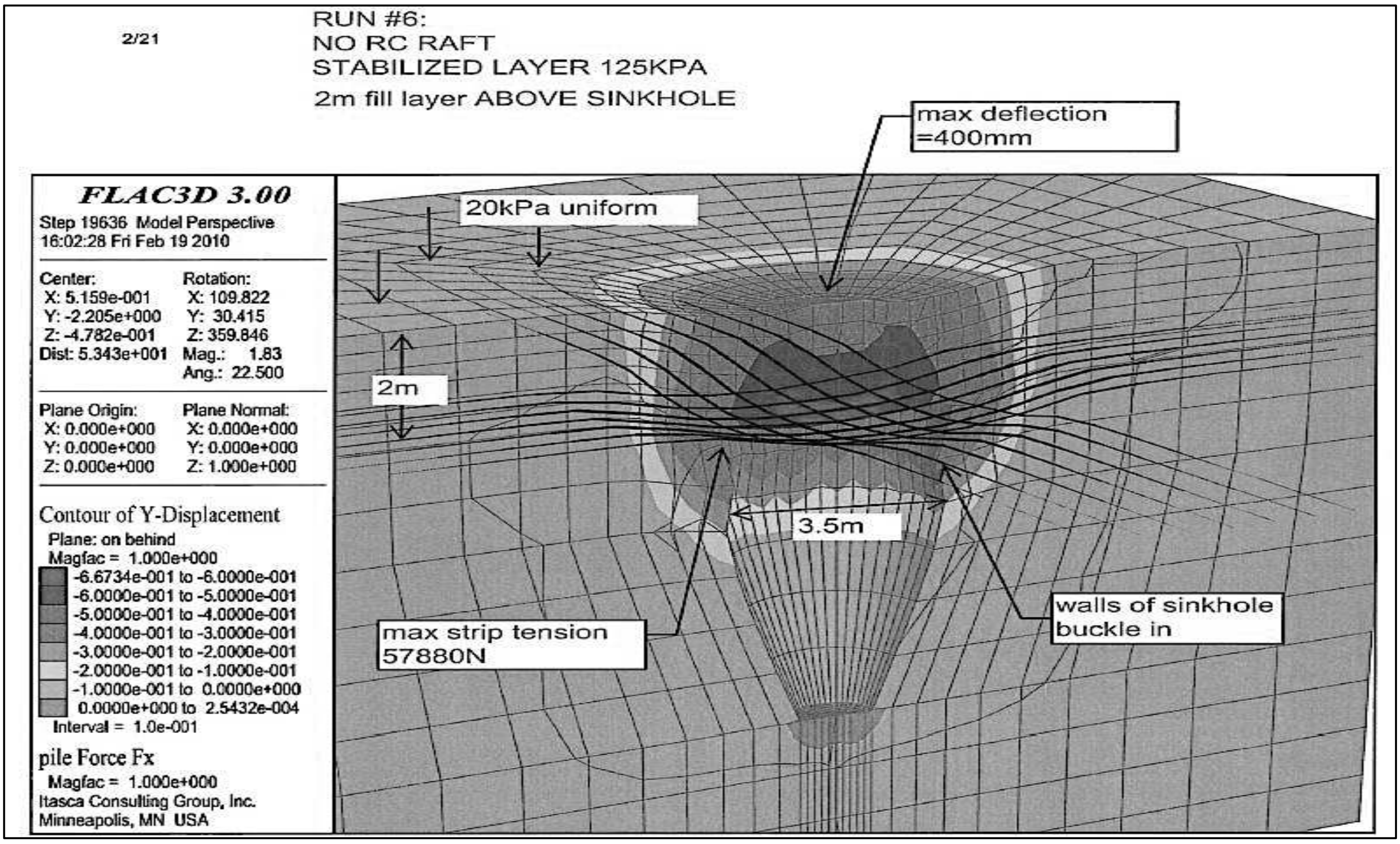


Figure 9. Run 6 - 3.5 m diameter without raft - Contours of Y displacements.

6 THE RUNS AND RESULTS – 10 M DIAMETER SINKHOLE

6.1 *Run for the formation of a 10 m diameter sinkhole (Fig. 10)*

The Catenary effect - in the event of a large diameter sinkhole developing as the deflection of the reinforcing strips increases, so the tension in the strips decreases. Provided the reinforcing strips can deflect by drag down on the sinkhole and yield, then equilibrium will be attained (Blight & Barrett 2009).

7 ANALYSIS OF RESULTS

The concept of the soil mattress acting as a slab with the steel reinforcing strips acting in tension and the fill above it in compression is confirmed.

The stabilised layer is probably not required since the 10 m diameter analysis used a strength for the stabilised layer of 250 kPa rather than 125 kPa with no effect.

Increasing the depth of the mattress from 2.0 m to 3.5 m was not advantageous since tension in the strips increased by 12,5 % without reduction of deflections.

The deflections with and without rafts meet the requirements.

The deflection at the centre of the 10m diameter sinkhole is acceptable.

The tension in the reinforcing strips after the sinkholes have formed is within design limits.

Table 1. Loading and results for 10m diameter sinkhole

Loading	Results
Loading Case 1: 20kPa live load surcharge over the entire area: Deflection at the centre = 367 mm.	Max deflection = 367 mm. Max tensile force = 20.51 kN
Loading Case 2: Loading Case 1 + 4 wheel loads 107 kN each. An equivalent of 200 kPa over 2 areas of 750 x 750 mm each. 2 wheels centred to hole. At passage of a truck over the hole, deflection and tension increase by only 1 to 2 %.	Max deflection = 371 mm Max strip tension = 20.85 kN
Loading Case 3: Loading Case 1 + 200 kPa over the entire surface of the hole. Equivalent to 140 wheel loads of 107 kN each. A deflection of 3000 mm at centre of the hole would take place prior to strip rupture. All strips reach yield. Before rupture a strain of 25 % would have taken place, therefore the large deflection serves as a warning.	Max deflection 3000 mm; Strips reach yield few strips start to break.

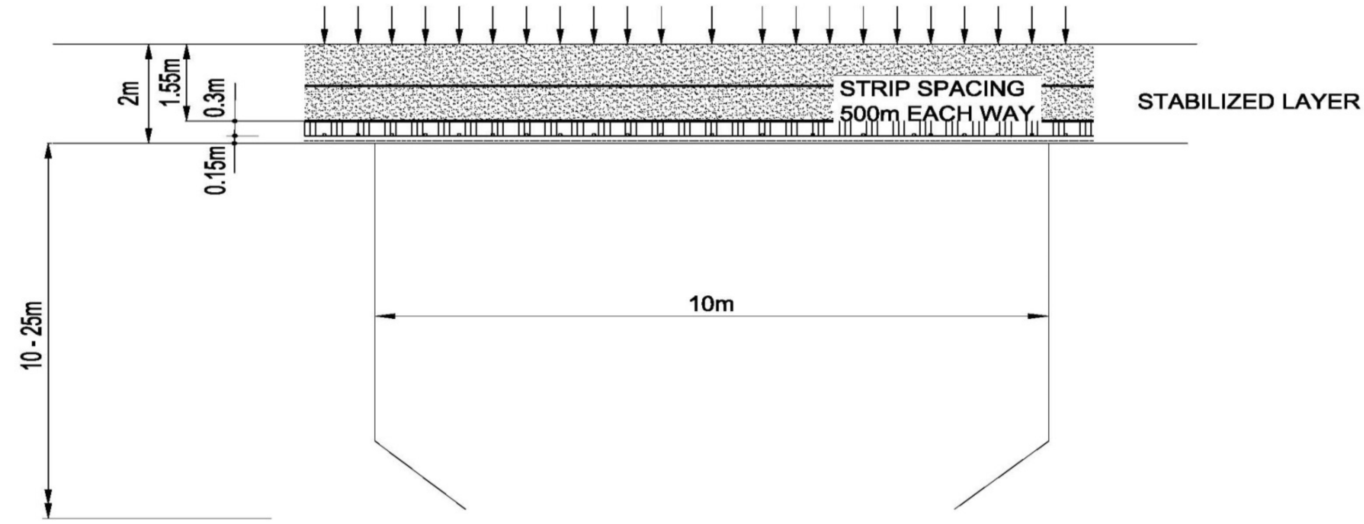


Figure 10. Section through 10 m diameter hole; cement stabilised layer directly on reinforcing strips

8 THE CONSTRUCTION

The reinforcing strips once connected provide a continuous mat across the site. The site varies in level. In order to allow connection of the 10m long double holed reinforcing strips, construction of the mat is required to start in one corner of the site and then spread across the site. A facing element is required around the periphery of the mattress to cater for a sinkhole developing on the edges of the site.

9 CONCLUSION

The analysis indicates that the reinforced mattress would meet the requirements of minimal settlement under the rafts; of acceptable settlement between the rafts for the occurrence of 2.0 m and 3.5 m sinkholes.

Should a 10 m diameter sinkhole occur then large deflections will occur long before strip rupture and prevent catastrophic failure.

The use of ductile steel reinforcing strips enables a soil mattress to span across relatively small sinkholes with little effect on structures founded on rafts and reasonable settlements on areas outside the rafts.

The mattress also prevents catastrophic failure and loss of life, should considerably larger sinkholes occur in the areas both covered and not covered by the reinforced concrete rafts.

Improvements could be made by reducing the thickness of the mattress and introducing cement stabilised fill between the strips and the surface. This would improve the shear transfer while still maintaining a large lever arm.

It is felt that this concept could contribute towards the development of land underlain by dolomites.

10 REFERENCES

Blight, G. & Barett, A. 2009. *Field Test of Catenary Net to Protect Traffic from Mining Subsidence*, Johannesburg, Civil Engineering Dec 2009, Reviewed by Highway Division ASCE.

Smith, A.C.S. 2001. Ground Improvement Using Steel Reinforcing Strips. *SAICE Geotechnical Division: Seminar on Ground Improvement Johannesburg, 8 & 9 October 2001.*