A ROAD EMBANKMENT FAILURE NEAR PENTALIA IN SOUTHWEST CYPRUS

J Hadjigeorgiou
Université Laval, Canada

E Kyriakou
Geological Survey Department, Cyprus

P Papanastasiou
University of Cyprus, Cyprus

ABSTRACT

The south west area of Cyprus has a long history of slope instability problems. The location and extent of these landslides has been influenced by ground morphology, geological structure and the presence of weak rocks and cohesive soils. The main triggering mechanisms have been precipitation and/or seismic events. Landslides have contributed to the decision to relocate villages and considerable efforts have been put into maintaining the integrity of the local transportation network. This paper uses a recent case study of road embankment failure near Pentalia in southwest Cyprus to review the available tools for the analysis of slope instability. It further demonstrates how the shear strength reduction technique can be used in a finite element analysis to better visualise the slope instability mechanism of a road embankment and provide a reliable tool in selecting appropriate remedial measures.

1.1 INTRODUCTION

The Paphos district in Cyprus has a long history of slope instability particularly in areas of high elevation. The geology of this part of the island is characterised by the Mamonia Complex, a very incongruent collection of allochtonous Upper Triassic to Lower Cretaceous sedimentary formations, and Upper Triassic mafic igneous rocks. The Mamonia complex also includes serpentinites and other metamorphic rocks. Also present in this area is the autochthonous Kannaviou formation of Campanian age comprising bentonitic clays and volcanoclastic sandstones. The major cohesive soil formations found in this area are commonly referred to as the melange and bentonitic clays.

Rainfall in Cyprus is mostly confined to the winter and spring months, with the highest average annual rainfall reported on the Troodos mountains. Cyprus is seismically active, particularly along the south coast.

There is strong evidence of prior landslide activity in this area. Pantazis (1969) cites several landslides in this area and identifies intensive rainfalls and the earthquakes of 1953 as the triggering mechanisms. These landslides have often resulted in partial or complete relocation of several villages. Northmore et al (1986) suggest that villages were traditionally constructed in the immediate vicinity to the contact of the argillaceous cohesive soils and chalks. These areas were selected due to the presence of natural water springs. Landslides were accepted as a fact of life in these areas with villagers responding to landslide damage by rebuilding in nearby areas.

Recent years have seen a major development in the infrastructure of this area, including several new roads linking the villages. This has led to a situation, whereby for a variety of reasons, roads were constructed in areas with a history of landslides. This has resulted in the need for reparations and the use of remedial measures to ensure the usability of the transportation network. This paper addresses a “typical” slope failure along the road linking Nata and Pentalia. The advantages of numerical modelling as a routine design tool for the analysis and design of road embankments are further elaborated.

2.1 THE NATA-PENTALIA ROAD

The road linking the villages of Nata–Pentalia-Panayia (along P453-P513) had already displayed signs of instability in January 2002 while the road was still under construction, Figure 1. The development of cracks in the road was attributed to higher than usual rainfalls and snowfalls. This is supported with reference to Figure 2, whereby unusually high precipitation was recorded in December 2001.

Figure 1. Indications of instability, 2003.

Despite some preliminary reparation measures (re-pavement of the asphalt) following the construction of the road, more cracks continued to appear. Following the rainfalls of winter of 2004 the signs of instability stretched along a patch of 340 m.

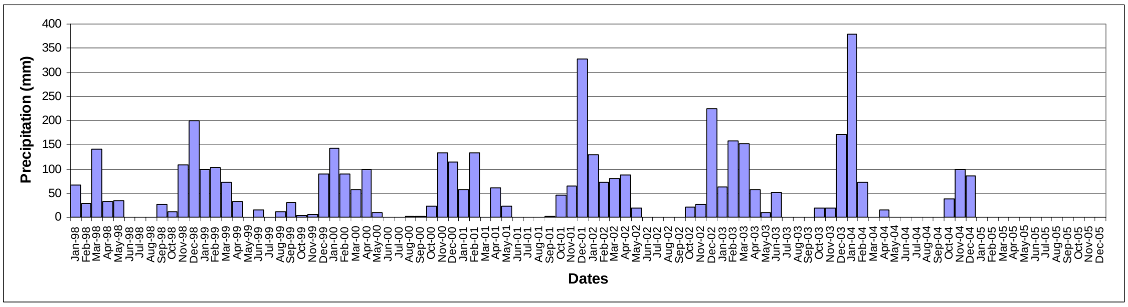

Figure 2. Rainfall data from the nearest recording station.

2.1.1 Preliminary Site Investigation

The first engineering geology investigations, following the continued instability of the road, revealed that the newly constructed road traversed an area with signs of old landslides. The geology along this part of the road is typical of the area. On the upper bank of the road there is talus material derived from the Lefkara formation. The talus material is composed of chalky and marl chalky fragments in a calcareous sandy silt matrix. The talus material is approximately 4 m thick and overlays a clay melange. The melange is a thick deposit of clasts derived from the Mamonia complex and embedded in an argillaceous matrix, characterised by high plasticity and low shear resistance. The overlying marls (talus) have a higher permeability than the underlying melange. It is thus possible that during the intense rainfall period, a perched water table develops along the contact of the two materials. This in itself may have detrimental effects on the stability of the embankment. This was recognised and one of the first remedial measures was the maintenance of drainage ditches along the road.

Preliminary investigations in 2004 suggested that, although it was possible that the road traversed older and deep failures the most likely slip surface was in fact shallow. This was based on limited inclinometer readings. At the time, the most likely slip surface was analysed using traditional limit equilibrium analyses. Based on a series of sensitivity analyses it was suggested that the slope could have been stabilised using a tie block or by reinforcing the slip surface using piles. The economics of these two options were based on the assumption that the critical slope surface was shallow. None of these remedial measures were implemented. Instead it was decided to survey the area to construct a terrain model.

In 2005, there were still no major remedial measures implemented, apart from localised repaving of the road to fill cracks. By the summer of 2005 there were clear signs of settlement and the development of further cracks, Figure 3. Following the construction of a terrain model and further observations it was recognised that a slip surface, at a distance 80 m further than the first analysis, was deeper than originally assumed. This has prompted further analyses and a re-evaluation of the overall strategy to return this road stretch to circulation.

Figure 3. Cracks along the Pentalia road, July 2005.

3.1 SLOPE STABILITY ANALYSIS

3.1.1 Limit Equilibrium Analysis

Limit equilibrium analyses are used on a routine basis for the analysis of slope instabilities. This is facilitated by easy access to user friendly and commercially available software that simplify data entry and allow for parametric studies to quantify the interaction of several parameters. The basic assumption of the limit equilibrium method is that a failure criterion is satisfied along an assumed failure surface (a line, a circular arc or any other irregular form). Consequently, the factor of safety of a slope is defined as:

$$F = \frac{\text{Shear strength of rock mass/soil}}{\text{Shear stress required for equilibrium}}$$

The main limitation of the limit equilibrium method is that it neglects the soil stress-strain relationship.

3.1.2 Numerical Modelling: The Shear Strength Reduction

Numerical techniques have been used for slope stability analysis for some time. The interest in the use of the Shear Strength Reduction (SSR) technique, Dawson et al (1999), is that it enables the finite element method to calculate factors of safety for slopes. The methodology is summarized by Lorig & Varona (2004). A basic assumption in the SSR finite element technique is that elasto-plastic strength is assumed for slope materials. Simulations are then run for a series of increasing trial factors of safety (f). Subsequently, actual shear strength properties: cohesion c and friction φ are reduced for each trial accordingly to the following equations:

$$\varphi^{trial} = \arctan\left[\left(\frac{1}{f}\right)\tan\varphi\right]$$

$$c^{trial} = \left(\frac{1}{f}\right)c$$

The trial factor of safety is then gradually increased until the slope fails. This is the condition when the factor of safety equals the trial safety factor. The advantages of the SSR finite element technique become evident once the method is compared to limit equilibrium methods. A relative comparison of numerical and limit equilibrium methods has been prepared by Lorig and Varona (2004) and is reproduced in Table 1. It is evident that the SSR is of particular interest for the analysis of road embankments such as those found in the Pentalia cases study.

Table 1. Comparison of numerical and limit equilibrium analysis methods, after Lorig and Varona (2004).

Analysis result	Numerical Solution	Limit Equilibrium
Equilibrium	Satisfied everywhere	Satisfied only for specific objects, such as slices
Stresses	Computed everywhere using field equations	Computed approximately on certain surfaces
Deformation	Part of the solution	Not considered
Failure	Yield condition satisfied everywhere; slide surfaces develop “automatically” as conditions dictate	Failure allowed only on certain pre-defined surfaces; no check on yield condition elsewhere
Kinematics	The “mechanisms” that develop satisfy kinematic constraints	A single kinematic condition is specified according to the particular geologic conditions.

4.1 Analysis of the Pentalia Road Embankment

The material properties used as the starting point for the slope stability analyses are summarised in Table 2. These values were based on past experience in this particular area, and where available, laboratory data.

Table 2. Material properties used as a starting block in the analysis.

Material	Cohesion (kPa)	Angle of friction (φ)	Unit Weight (kN/m3)	E (MPa)*	ν*
Talus	10	29	23	30	0.30
Clay mélange	0	27	20	14	0.40
Compacted Road fill	0	39	23	75	0.35

*Estimated

4.1.1 Limit Equilibrium Analysis of the Pentalia road failure

The first analysis at this site was reported by Kyriakou (2003). Based on the available information at the time, the critical failure surface was relatively shallow along section A-A. The stability analysis at the time focused on the relative benefits of introducing a buttress at the base of the landslide. This would have to be extended along the full length of the embankment that showed signs of instability, close to 340 m. This would have been adequate provided the slip surface was shallow. Furthermore, it would have been necessary to secure the rights to construct the buttress. Other immediate recommendations included the development of appropriate draining measures and concrete ditches along the road embankment. The critical slip surface yielded a factor of safety of 1.14 under dry conditions.

The investigation of 2005 recognised that a slip surface further up the road, section B-B, was deeper than previously assumed. It was evident that it would be much more difficult and expensive to stabilize. The critical slip surface was found to have a factor of safety of 0.98 using Bishop's Simplified Method.

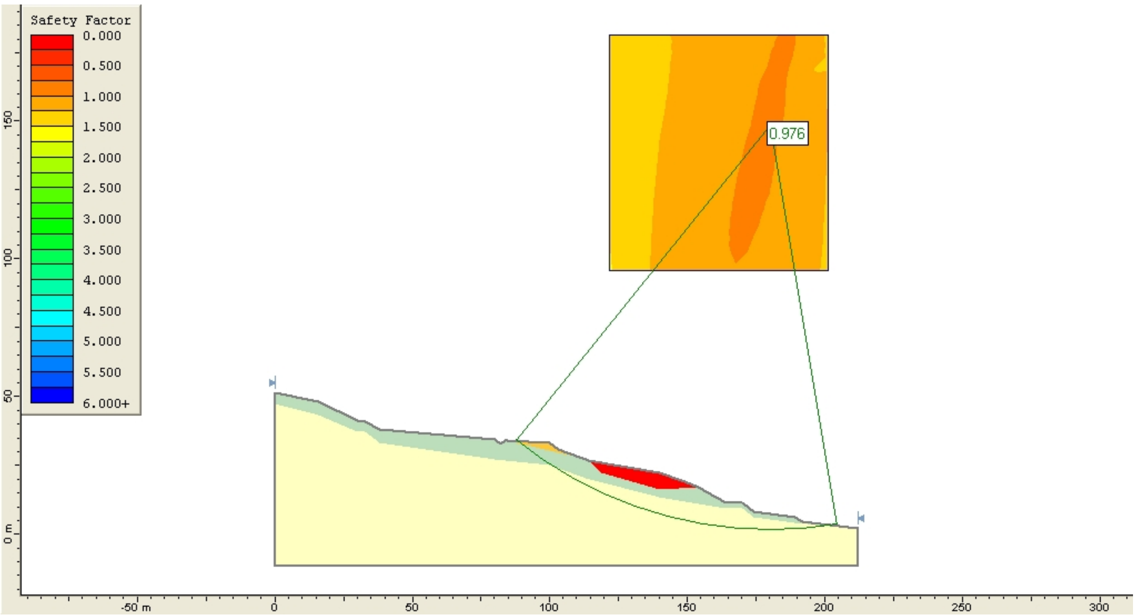

Figure 4. Limit equilibrium analysis of section B-B.

There are several issues here regarding both analysis and practical design considerations. The factor of safety is dependent on the method of calculation with the Bishop's simplified method resulting in factors of safety relatively higher than Janbu's method. Arguably the success of the method relies in capturing the critical slip surface. It was recognised that there were important benefits to be derived by a comprehensive engineering geology investigation prior to localization of the road in this area. The timing and implementation of any remedial measures could have arguably mitigated the results of the observed instabilities.

4.1.2 Strength Reduction Factor Finite Element Analysis of the Pentalia Road Failure

The same geometrical models used in the limit equilibrium analysis were introduced into a finite element analysis package Phase2 Rocscience (2005). This is a powerful and flexible computer package which has the strength reduction factor technique integrated into the finite element analysis and interpretation modules. Hammah et al (2005) provide an excellent review of practical considerations associated with the use of the Strength Reduction Factor in Phase2. In particular, they demonstrated that the method can provide comparable results of calculated factors of safety with limit equilibrium approaches provided:

- the modulus of Elasticity and Poisson's ratio are comparable (in fact they suggest using the same values, if wishing to duplicate the results of limit equilibrium analysis)
- a dilation angle equal to zero is used, and
- the elastic-perfectly plastic assumption for post peak behaviour is employed.

It was further recognized that although variations in the modulus of Elasticity and Poisson's ratio may not be have a major impact on the calculated factors of safety, they have significant influence on the magnitudes of the computed deformations.
The slope configurations used for the limit equilibrium analyses were also used for the finite element analyses. The strength reduction factor yielded a critical value of 1.32 for section A-A and 0.92 for section B-B. It should be noted that these values are for dry conditions. Plotting the maximum shear strain provides a good indication of where slip is developing for a given Strength Reduction Factor. This is illustrated in Figures 5 and 7. In reviewing the status of the slope for different SRF it is possible to visualize the progression of failure within the slope. The zone of failure is also visualised by plotting a total displacement graph. Figures 6 and 8 plot the total displacement concentrations and the resulting deformed mesh. The resulting slope geometry closely resembles the observed field conditions.

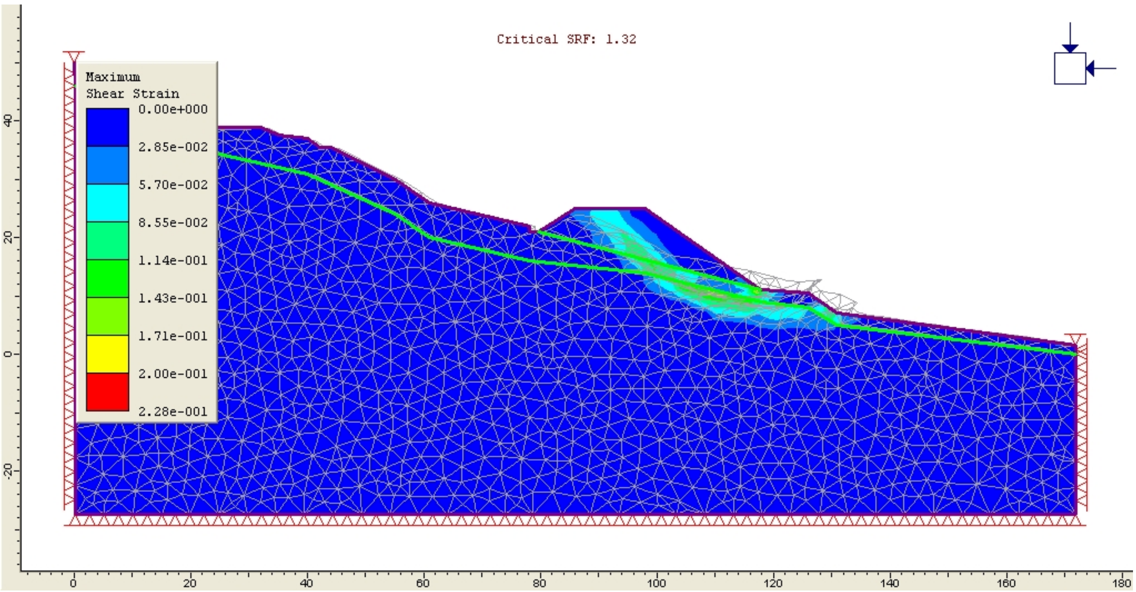

Figure 5. Section A-A shallow failure illustrating the development of maximum shear strain concentrations.

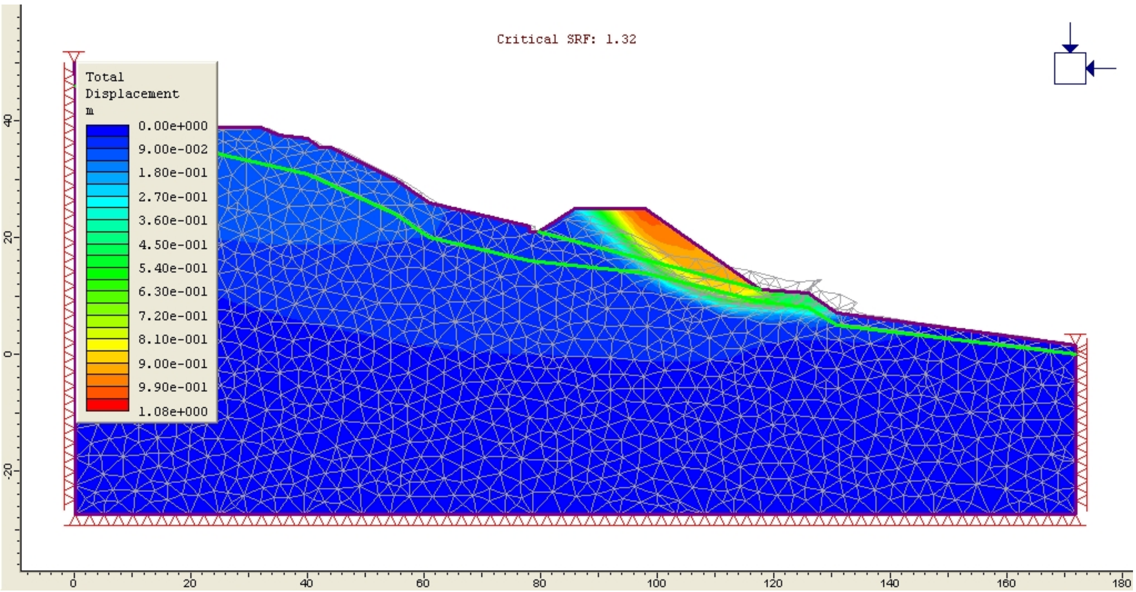

Figure 6. Section A-A shallow failure illustrating the development of total displacement concentrations.

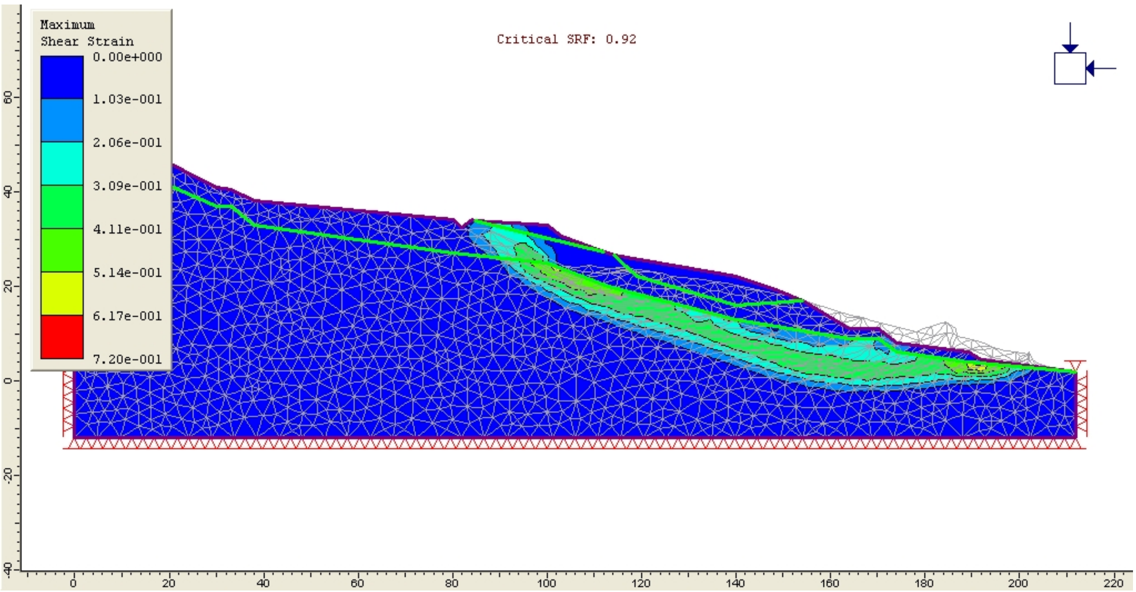

Figure 7. Section B-B illustrating the development of maximum shear strain concentrations.

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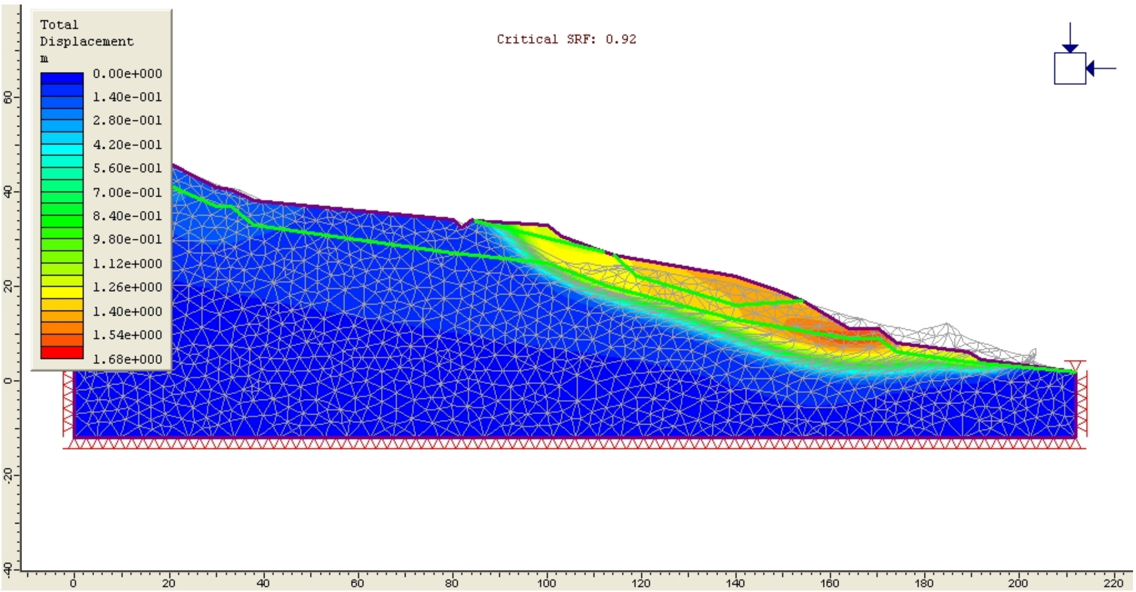

Figure 8. Section B-B deep failure illustrating the development of total displacement concentrations.

The results of the simulations of section B-B clearly demonstrate that the failure surface is much deeper than what was observed and calculated by the limit equilibrium and numerical models for Section A-A. This has significant consequences in developing a strategy for the support of the slope. A deeper failure surface would require a bigger volume of buttress and would probably require more land to be expropriated for these purposes. The use of reinforcing piles as discussed in the earlier discussions for the stabilization of this embankment was also a more expensive option. In order for the piles to be successful in strengthening the slip surface they would have to intersect it. In fact an economic analysis of the associated costs for the different remedial measures suggested that in light of the new information, serious consideration would be given to re-routing this stretch of the road.

5.1 CONCLUSIONS

This paper presents a typical road embankment failure in Southwestern Cyprus. There are several issues associated with interpreting the landslide but also with the field investigation. In retrospect, it would have been beneficial if a comprehensive engineering geology investigation had preceded the marking of the highway in this particular area. Furthermore, once the early instability signs were noted it may have been advantageous to respond in a more timely fashion.

In this particular case the shallow slip surface was the first to be recognized. If stabilization measures had been enacted immediately they may have succeeded in stabilizing the road embankment. Most probably, however, the deeper slip surface would have been reactivated sooner or later.

This case study has illustrated that a finite element analysis can be used as a routine tool for slope stability analysis. This has been made possible by the development of robust, user friendly computer software packages. In principle the ease of data exchange between the two software packages employed in this analysis is a major advantage. The most significant benefits however are derived by the use of the SSR finite element technique to illustrate a more realistic representation of the failure mechanism. The presented analysis can easily be extended to consider the influence of realistic flow pattern as a result of rainfalls, seismic events etc. Furthermore, the impact of different remedial measures can be quantified and attention given to the associated implementation costs.

6.0 ACKNOWLEDGEMENTS

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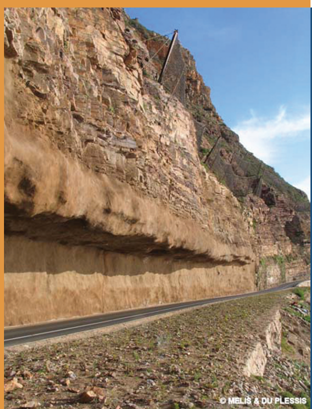

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