Figure 1 Site locality

An investigation into the stability of the Ring Road lateral support system adjacent to the construction of UCT's new engineering building

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INTRODUCTION

In 2010 the University of Cape Town (UCT) embarked on a three-year capital expenditure programme valued at nearly R1 billion. A considerable component of this expenditure programme was the construction of the New Engineering Building (NEB), on the slopes of Devil's Peak, which commenced in January 2011. The NEB was to replace the structure housing the Civil Engineering Department laboratories. This project required a multi-staged demolition of the structure, in conjunction with the initiation of construction. Furthermore, extensive bulk excavations were required in order to accommodate the proposed basement level of the NEB earmarked for the new Civil Engineering Department laboratories.

The bulk excavations for the basement level raised slope stability concerns relating to the site's western boundary. The western boundary of the site supports Ring Road – a busy internal road of UCT – by means of a tapered gravity retaining wall. The wall supports a 6.3 m backfill at its highest point. During the planning and design phase of the NEB it was established that the stability of this retaining structure would be undermined by the excavations extending 3.3 m below the toe of this structure. Hence, an additional lateral support system was designed and constructed by Esorfranki before excavations took place, in order to provide the required stability to the slope once excavations commenced.

These slope stability concerns led to an independent investigation, led by the University of Cape Town's Civil Engineering Department and centred on good excavation practice, to assess the performance of the Ring Road lateral support system in stabilising the western boundary. This was carried out in light of the growing need for sustainable land use, whereby the expansion of underground space is regarded as a suitable solution (Goddard 2004). Furthermore, recent excavation failures, such as the collapse of Singapore's Nicoll Highway in 2004, formed the setting to the investigation into the NEB earthworks' influence on the neighbouring lateral support system. Extensive research into excavation failures, especially by Sowers (2004), Chen *et al* (2000) and Gue & Tan (2004), found that inadequacy in design was the main contributing factor to excavation failures. This emphasised the importance of using thorough design and analysis techniques during the design of excavations in order to prevent failure. It is against this backdrop that the investigation into the performance of the Ring Road lateral support system adjacent to the NEB was launched.

The primary objective of this study was to provide insight to the question, "How was the stability of the NEB site's western boundary affected by the excavation works?" This was assessed by a slope stability analysis using (1) limit equilibrium (LE) techniques, and (2) the Shear Strength Reduction (SSR) technique. The SSR method involves the systematic use of Finite Element (FE) analysis to determine a Shear Strength Reduction Factor (SSRF), or factor of safety which brings the slope to the verge of failure (Hammah *et al* 2005). This is done by reducing the strength of respective materials of the slope by the SSRF until the FE analysis does not converge – giving the critical SSRF, which is effectively regarded as the global factor of safety for the respective slope.

The SSR technique was used to supplement and provide insight into the output given by the conventional LE techniques, especially with regard to the stress-strain behaviour of the respective materials. The necessary modelling was carried out using two software packages developed by *Rocscience*, under licence from Kantey and Templer Consulting Engineers. *Slide* was used to conduct the LE slope stability analysis. This is a powerful slope stability package, capable of assessing numerous material models, as well as structural elements such as ground anchors and retaining walls. *Phase²* – a two-dimensional FE program – was used to supplement the output given by the LE analysis. This was done in order to assess the material behaviour and its subsequent response to the ongoing excavations and loading. The stability of the Ring Road lateral support was assessed by comparing the stability of the system before and after excavations took place. This resulted in a thorough geotechnical analysis, which is outlined in the sections to follow.

SITE CHARACTERISATION

Geological conditions

Based on published geological data, the area is known to be underlain by a varying thickness of transported material emanating from the slope to the west, followed by residual Malmesbury Group shales of the Tygerburg Formation (Brink 1985). This geological information was confirmed upon sub-surface investigation by Kantey and Templer Consulting Engineers (2010). A geotechnical investigation was conducted by drilling four boreholes across the site and assessing the substrata by means of Standard Penetration Tests (SPT) and core-logging. Three distinct material profiles were found, namely, (1) fill, (2) transported material and (3) residual Malmesbury Group material. The description of these layers is summarised in Figure 2.

Depth (m)	Brief Description
2.5	Fill material, consisting of sand and brick fragments. Sign of feruginisation – highlighting seepage from the slopes to the west of the site. [FILL]
14.7	Colluvial material, consisting of sandstone boulders supported in sandy silt matrix. Medium dense to dense with depth. [TRANSPORTED]
16	Reworked weathered Malmesbury Group material – fissured clayey silt (ML). Stiff to very stiff with depth. [REWORKED RESIDUAL]
	Intact weathered Malmesbury Group material – clay silt (ML). Very stiff. [RESIDUAL]

Figure 2 Summary of material profile

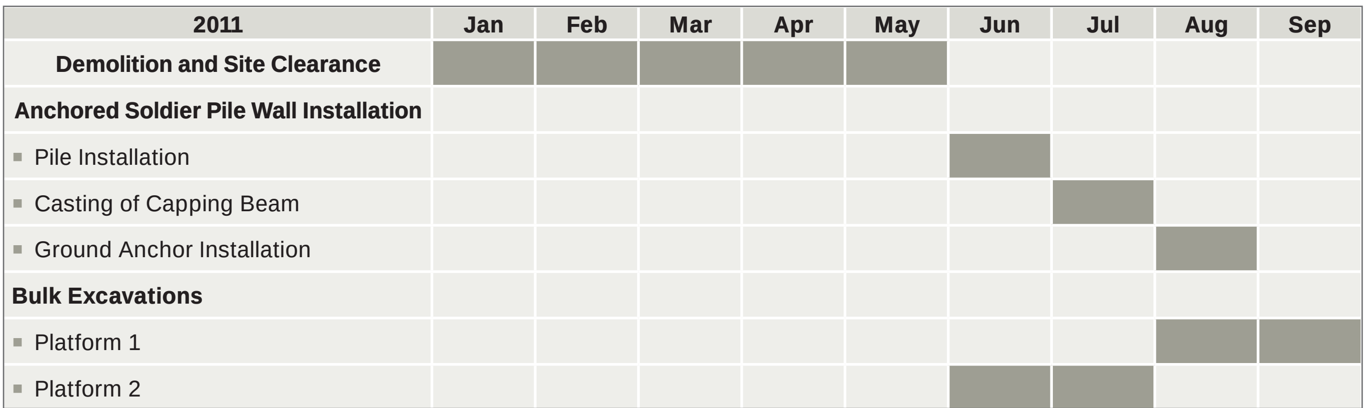

Figure 3 Bulk excavation programme

Staging of excavation process

The NEB complex was to be constructed on the same footprint as the former Civil Engineering Department laboratories. This required the demolition of the respective buildings before excavation could commence. Furthermore, based on the findings of the geotechnical site investigation, the western boundary required additional lateral support. The details of these processes are presented below, and the bulk earthworks programme is given in Figure 3.

Demolition of Civil Engineering Department laboratories and site clearance

The first stage of construction involved the demolition of the Civil Engineering Department's laboratories. This process took approximately 5 months to complete, and involved the following:

- Demolition of the Civil Engineering Department's laboratories and the foundations
- Removal of all rubble from the site
- Removal of former stormwater drainage systems located on the site
- Relocation of trees
- Establishment of an initial ground level (IGL) of 121.65 m above mean sea level (AMSL)

Installation of additional lateral support on western boundary

The installation of the additional lateral support on the western boundary was a three-month process, beginning in June 2011. An anchored soldier pile wall was deemed the most appropriate retaining system for the NEB site by the design consultants. This included the following components:

- 750 mm diameter, 17.0 – 20.0 m long cased auger piles
- 300 mm diameter, 7.75 m rotary percussion piles
- 1.0 m wide, 1.2 m deep capping beam
- 16.5 m Titan 52/26 permanent ground anchors
- Steel mesh and gunite arch system

The piles were arranged with sets of three 300 mm diameter piles in-between pairs of 750 mm diameter piles. The 750 mm diameter piles were used to support 5 MN column working

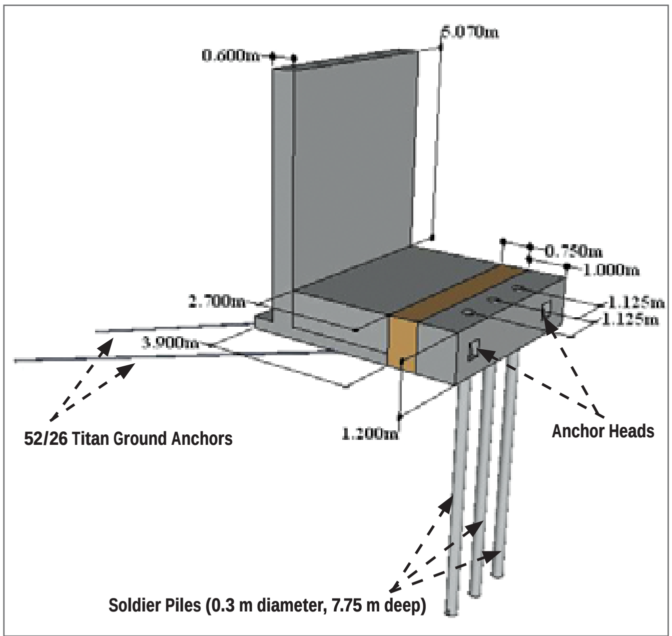

Figure 4 View of the anchored soldier pile wall

Figure 5 Completed bulk earthworks and the commencement of footing excavations

loads. These piles were modelled in Plaxis, by Esorfranki, and sized according to a 2.5 MN load supported by each 750 mm diameter pile. Although designed primarily as load bearing, the 750 mm diameter piles provided considerable stiffness to the lateral support system, which ultimately allowed the use of the 300 mm diameter piles.

The initial design of the lateral support system actually comprised 600 mm diameter continuous flight auger (CFA) piles and 750 mm diameter cased auger piles, with alternating pairs. However, upon the commencement of boring, it was found that CFA piles were not suitable, due to the frequent occurrence of extremely large boulders. This resulted in the set of three 300 mm diameter rotary percussion piles replacing the pair of 600 mm diameter CFA piles in-between the 750 mm diameter piles.

Once the installation of the piles was complete, the capping beam was constructed to provide extra rigidity to the soldier pile wall, and it provided a base upon which ground anchors could be stressed (Figure 4). The ground anchors were installed to minimise the deflection of the pile wall. This was deemed necessary to minimise the possibility of eccentric loads forming at the column-capping beam interface, and to reduce the bending stresses in the soldier piles. The installation of the ground anchors began once the capping beam had reached sufficient strength to resist the ground anchor stresses.

Steel mesh gunite arches were adopted to retain the soil in-between the soldier piles. Wick drains were installed behind these arches to convey seepage to a drain at the basement floor slab level. The gunite arches were constructed after the anchors had been installed and the necessary excavations completed.

Table 1 Material parameters

	Colluvial Material	Reworked Malmesbury	Intact Malmesbury
Bulk Density, γ *(kN/m³)*	18	18	18.5
Friction Angle, ϕ' (°)†	36	28	28
Cohesion, *c' (kPa)* †	2	15	25
Elastic Modulus, *E (kPa)*	25 000	20 000	20 000
Poisson's Ratio, ν	0.35	0.3	0.3
† Effective Parameters			

Bulk excavations

The bulk excavation process involved the establishment of two platforms – Platforms 1 and 2 – over a period of four months. The two platforms were established at different levels in order to accommodate basement levels and the pad footings upon which the NEB was to be founded.

The excavation works were carried out by Caterpillar 330C excavators. Platform 2 was excavated first as these excavations did not interfere with the installation of the additional lateral support to the western boundary. Excavation processes were carried out on portions of Platform 1, but Platform 1 was only completed after the ground anchors had been installed. Figure 5 illustrates the completed bulk earthworks.

SELECTION OF MATERIAL PARAMETERS

The material parameters used to conduct the relevant modelling in this study are illustrated in Table 1. It should be stressed that this investigation was independent of previous design and planning processes conducted by the consulting engineering teams. Therefore, the soil parameters listed below were derived during this investigation, and were not necessarily the same parameters used by the design engineers. The bulk density of all three materials was derived from laboratory testing. The Mohr-Coulomb shear strength parameters for the colluvial material were determined through back-analysing an exposed cutting on the site. The Mohr-Coulomb shear strength parameters for the reworked and intact weathered Malmesbury Group material were determined from relevant literature and case studies, with considerable reference to Brink (1985) and Parrock & Du Plessis (2010). The elastic material parameters were derived from relevant literature, with special reference to Sabatini *et al* (1999) and Kulhawy & Mayne (1990).

RESULTS

Table 2 gives the slope stability results from the different methods of analysis conducted on the Ring Road lateral support. These results are summarised and shown graphically in Figure 6. It is evident from these results that the system was sufficiently safe both before and after excavation. This is based on factor of safety and SSRF values greater than 1.50. Furthermore, the stability improved with the construction of the tied back wall and excavation of the respective soil.

On a qualitative level, the importance of the pile wall was illustrated by this analysis. The circular shear failure results indicate that the overall failure mode was critical. However, the analyses conducted using non-circular shear surfaces show that the most likely mode of failure was through the ground anchor. An important observation of this was the shear surfaces extending below the pile wall despite breaching the ground anchor. This highlighted the importance of the pile wall in maintaining stability. This also emphasised the increased stability of the system by displaying that a failure of the soil body through the anchor was more probable than an overall failure of the system.

The circular and non-circular shear failure surfaces were superimposed onto the FEM SSR results as illustrated in Figures 7 and 8 by a red and orange dashed line respectively. This was done in order to compare the FEM SSR results directly to the minimum shear surfaces discovered during the LE analysis. Figure 8 shows the development of two distinct shear strain zones. The most prominent shear strain zone coincided closely to the non-circular slip surface yielded by the LE analysis. The circular shear surface also followed a band of less prominent shear strain recognised by the FEM SSR analysis. Furthermore, Figure 8 depicts the effect of the pile with significant shear strain in front of the pile wall, but a reduced area of shear strain behind the toe of the wall. This demonstrates the mobilisation of the shear stress by the pile wall and how this stress is transferred to the soil in front of the wall.

The FEM SSR results illustrated the effectiveness of this technique, especially when combined with conventional LE methods. With reference to Figure 6, the LE result showed an improved factor of safety with the construction of the pile wall, but the FEM SSR results did not. The decrease of SSRF values between the two cases is likely to be due to the increased surcharge loading behind the wall as a result of a construction crane. The benefit of the FEM SSR technique is given here, as the results demonstrated the behaviour of the material behind the lateral support system in response to the increased surcharge loading from the retained soil and crane loading. This was important, as it illustrated the system's stability as a function of its geometry, strength parameters and loading, in terms of the material's response to stress. The FEM SSR technique essentially modelled a progressive failure of the slope, and in doing so, highlighted key weaknesses in the material which arose from the system's geometry and loading. Such an analysis is not possible to model using LE techniques, as inter-particle material interactions are not assessed. Furthermore, LE methods are unable to model the interaction between structural elements, such as the anchored soldier pile wall and the supported soil. FEM methods can, and are able to accurately predict the structural elements' interaction with the retained material, including key parameters such as anchor forces, deformation, shear, bending and axial stresses.

CONCLUSIONS

The analyses conducted on the western boundary of the NEB bulk excavations found the Ring Road lateral support system to be stable. This conclusion was derived from slope stability analyses, using numerical methods, conducted on the Ring Road lateral support system. The Ring Road lateral support system formed the western boundary to the NEB site.

The slope stability analysis conducted on the Ring Road lateral support system showed that the system was stable, based

Table 2 Slope stability results

	Before Excavation		After Excavation	
Analysis	**CSF‡**	**NCSF†**	**CSF**	**NCSF**
Fellenius	1.799	1.326	1.937	1.322
Simplified Bishop	2.235	1.786	2.319	1.851
Simplified Janbu	1.815	1.663	1.695	1.794
Corrected Janbu	1.976	1.811	2.137	1.941
Spencer	2.237	2.197	2.354	2.316
Average	**2.012**	**1.757**	**2.142**	**1.845**
SSRF•	**2.39**		**2.28**	

‡ Circular Shear Failure Analysis | † Non-circular Shear Failure Analysis | • Shear Strength Reduction Factor

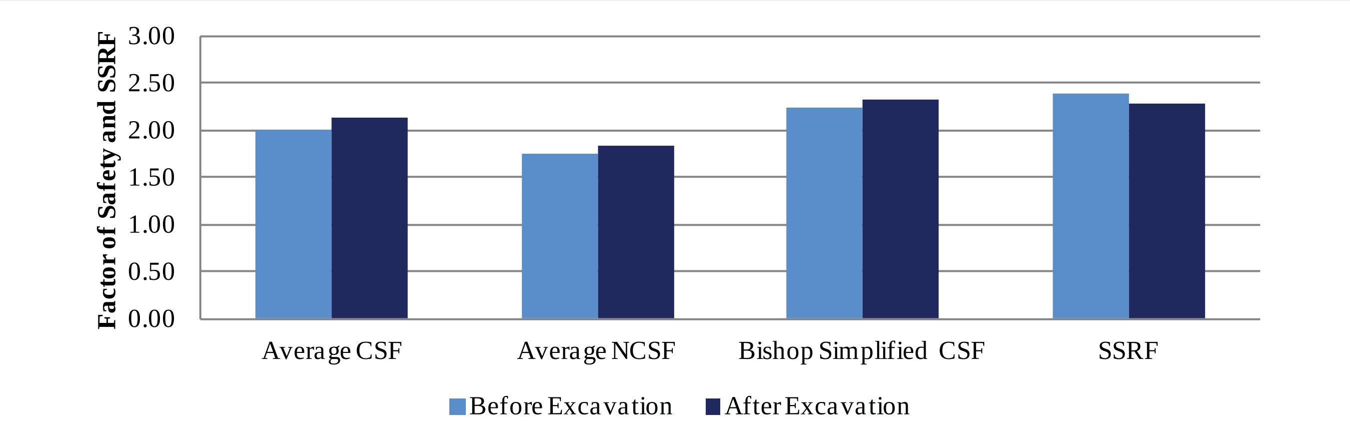

Figure 6 Comparison of slope stability results

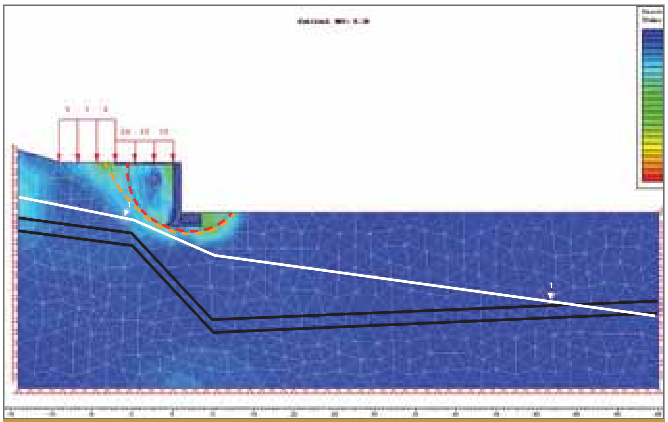

Figure 7 FEM SSR slope stability results – after demolition, but before excavation

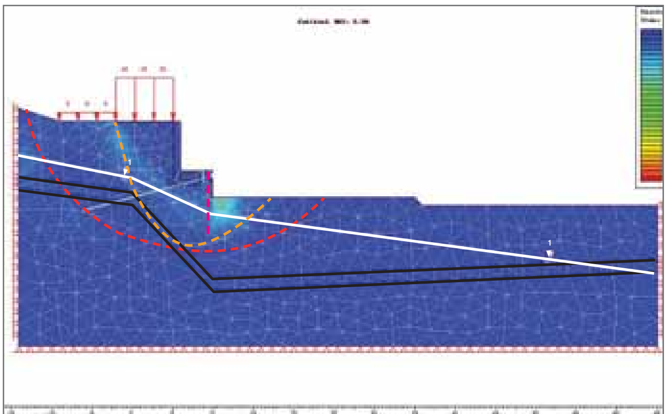

Figure 8 FEM SSR slope stability results – after excavation

on the factor of safety and SSRF values produced from the LE and FEM SSR analyses respectively. The section of the Ring Road lateral support that was modelled yielded factor of safety and SSRF values greater than 1.50. Although the SSRF values were found to be adequately high to assure the safety of the system, the development of a zone of increased shear strain was found in all the FEM SSR analyses conducted on the Ring Road lateral support system. It is likely that this shear zone was influenced by the surcharge loading behind the wall. This highlighted the usefulness of combining LE methods with the FEM SSR method in assessing slope stability. Furthermore, this investigation emphasised the effectiveness of using FE methods in the design of lateral support systems. This was based on FE methods being able to model the response of the materials to stress, as well as the interaction between the retained soil and the support system.

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NOTE

The list of references is available from the editor.

The analyses conducted on the western boundary of the NEB bulk excavations found the Ring Road lateral support system to be stable. This conclusion was derived from slope stability analyses, using numerical methods, conducted on the Ring Road lateral support system. The Ring Road lateral support system formed the western boundary to the NEB site