The effect of declining water levels on the stability of riverbank slopes

Matthew Schiller and Shane Wynne
School of Civil and Environmental Engineering, University of Adelaide

Abstract

The following research continues from recent studies from Adelaide University, which used unsaturated soil mechanics and further advanced the understanding of climatic influences on long term soil behaviour. Recent upgrades to computing technology allow SoilVision software to accurately model long term slope stability. Two software packages where used, SVFlux for seepage modelling and SVSlope for calculating slope stability. For the case of a lowering water level along a riverbank; the shear strength along failure plane, in unsaturated zone, increases as water level decreases, and collapse of riverbank is due to other mechanisms, not rotational failure. The research presented examines modelling the effect of declining water levels on the stability of riverbank slopes. Where; climatic factors, geometry of the slope, material properties of the soil and time taken to vary water level all influenced the stability of the slope. The contribution of soil suction to shear strength was considered. The drying of the soil to increase the shear strength and wetting of the soil to decrease the shear strength, However the influence of unsaturated shear strength was lessened by the presence of a high groundwater table. As the method of unsaturated shear strength decreases the likelihood of a conservative solution it is important to ensure that the model parameters are accurate as this can lead to underestimated factors of safety.

1. INTRODUCTION

The theory of unsaturated soil mechanics and associated design parameters has been developing for the past few decades. However, due to their complex nature they have been omitted from routine geotechnical design. Similar to other aspects of geotechnical design, slope stability has been based using the principles of saturated soil mechanics. In recent times, it has become feasible with upgrades to computing technology to evaluate shear strength based on unsaturated soil mechanics which optimises the solution using the principles of effective stress.

Advances in computing technology have lead to the ability to undertake long term analyses using complicated numerical software, Jones et al. (2009) stated that the software package SVFlux is capable of solving the combined effect of soil water movement due to suction and climate conditions using finite element methods. SVSlope has the ability to incorporate the solution obtained in SVFlux with common methods to determine the stability of a slope. Using SVOffice, Jones et al. (2009) showed the advantage of the use of unsaturated soil mechanics for optimising the design of earth retaining structures in Adelaide’s semi-arid conditions.

The main objective of this research was to develop a model that explained the reason behind slumping occurring previously along riverbanks of the River Murray in South Australia, like at Long Island Marina, Murray Bridge reported by Frazer (2009). The research was undertaken using SVOffice by investigating various individual effects of:

- unsaturated soil conditions,
- changing river water level,
- precipitation and evaporation along the bank,
- critical slopes (geometry), and
- material parameters of the soil.

2. THE NATURE OF UNSATURATED SOILS

The structure of unsaturated soils

Fredlund (2006) proposed that the entire soil profile that is subject to negative porewater pressure be referred to as the unsaturated zone. The unsaturated soil profile is continuous between the fully saturated and dry phases. Jones et al (2009) showed that climatic variation, permeability and soil suction all govern the availability of moisture and found that the degree of saturation is a highly non-linear function of moisture availability, depth and time.

The influence of climate on unsaturated soils

Fredlund et al. (1993) states that climate affects whether a soil is saturated or unsaturated. Precipitation provides a downward flux into the soil. Evaporation or evapotranspiration produce an upward flux out of the soil. The net flux, the difference between the two flux conditions, dictates the porewater pressure conditions in the soil. Fredlund et al. (1993) states in arid and semi-arid regions evaporation from the ground surface exceeds precipitation. The desaturated soil located above a deep groundwater table has a negative porewater pressure. Wetting the desaturated soil can cause the volume and shear strength of the soil to change due to the increase in porewater pressure, depending on the type of soil.

Jones et al. (2009) showed that the software package SVFlux has the capability to incorporate climatic parameters, such as precipitation and evapotranspiration, into moisture flux models. SVFlux, a finite elements package, models the behaviour of a core of soil under the influence of climatic-type events, using material properties and both initial and boundary conditions. The inclusion of climatic events in modeling is vital due to the large influence of moisture content on unsaturated soils.

Soil suction

Jones et al. (2009) suggest that soil suction can be expressed as the soil's attraction for pure water. A saturated soil is in a state of equilibrium such that free water is able to flow through the soil. Unsaturated soils have yet to reach this saturated equilibrium and as a means to equilibrate they draw free water. This drawing of water creates a suction force between soil particles referred to as negative pore-water pressure, or soil suction. For a soil with low water content, soil suction is high and vice-versa. Soil suction, or total suction, is the combined action of matric and osmotic suction, and is expressed in Equation 1.

$$\Psi = \Psi\mathrm{m} + \Psi\mathrm{o} \qquad (1)$$

Where, Ψ is the total soil suction (kPa); Ψ_m is the matric suction (kPa); and Ψ_o is the osmotic suction (kPa)

Soil-water characteristic curve (SWCC)

The plot of moisture content versus soil suction is known as the soil water characteristic curve (SWCC) as illustrated in Figure 1. The soil-water characteristic curve is essential to the application of unsaturated soil mechanics. Jones et al. (2009) stated that the SWCC represented a 'fingerprint' for a soil, as the soil's attraction for water is unique for each soil.

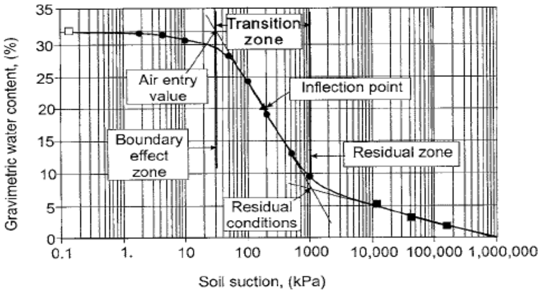

Figure 1 - Soil-water characteristic curve (Fredlund, 2006)

Fredlund and Xing (1994) formulated an important SWCC equation. Equation 2 relates gravimetric water content to soil suction in relation to parameters a, n, m, h.

$$W_w = W_s\left[1 - \frac{ln\left(1+\frac{\psi}{h_r}\right)}{ln\left(1+\frac{10^6}{h_r}\right)}\right]\left[\frac{1}{\left[ln\left[\exp(1)+\left(\frac{\psi}{a_f}\right)^{nf}\right]\right]^{mf}}\right] \qquad (2)$$

Where; a_f is a soil parameter related to the air entry value of the soil; nf is a soil parameter related to the rate of water extraction from the soil once the air entry value has been exceeded; mf is the soil parameter related to the residual water content; and h_r is the suction at which residual water content occurs.

The movement of water through an unsaturated soil

Fredlund (1993) highlighted the major difference between the flow of water in saturated and unsaturated soils as the difference in the coefficient of permeability.

The coefficient of permeability is assumed to be constant for saturated soils and the rate at which soil suction draws water through a soil for unsaturated soils which changes with degree of saturation. Jones et al. (2009) identified the soil suction gradient as the driving force which water moves through an unsaturated soil. They showed empirical based formulas have been derived to fit a mathematical function to represent the variation of permeability with water content.

The Fredlund and Xing (1994) estimation was used for purposes of research. It was devised in conjunction with the formulation of the SWCC. Equation 3 shows the Fredlund & Xing estimation.

$$k_r(\psi) = \frac{\int_{ln(\psi)}^{b}\frac{\theta(e^y)-\theta(\psi)}{e^y}\theta\prime(e^y)dy}{\int_{ln(\psi aev)}^{b}\frac{\theta(e^y)-w\theta}{e^y}\theta\prime(e^y)dy} \qquad (3)$$

Where, θ is the volumetric water content; θ' is the derivative of Eq. 3 with respect to ψ; b is ln(1,000,000); and aev is the air-entry value.

The shear strength of an unsaturated soil

Jones et al. (2009) investigated various studies showing the link between soil suction and shear strength derived from measured matric suction values. Jones et al. (2009) found that the saline porewater found in Adelaide clays could allow unsaturated soils to have osmotic suction representing up to 80% of total suction. They presented Equation 4, which includes the effect of osmotic suction.

$$\tau = \left(c' + \psi_t \tan\varphi^{bt}\right) + \left(\sigma'_n \tan\varphi'\right) \qquad (4)$$

Where: τ is the total shear strength (kPa); c' is the effective cohesion (kPa); ψ_t is the measured total suction (kPa); φ^{bt} is the contribution of total suction to shear strength (°);σ'_n is the net normal stress minus the pore pressure (kPa), and φ' is the effective friction angle (°).

3. MODELLING SLOPE STABILITY

Current practice of modeling the stability of a slope

Duncan (1996) compared all methods of calculating the stability of slopes. He referenced two different types of analyses, namely the limit equilibrium and finite element approaches to the stability of slopes. The finite element method (FEM) of analysis is not commonly used to solve slope stability problems but has various other geotechnical uses. Duncan (1996) states that Limit Equilibrium methods are preferred in current practice because of the extended amount of time needed to perform the FEM analysis. Stability analyses involve the solution of many iterations, completing the process for many different slip circles until the designing engineer is confident the most critical slopes are analysed.

Stability analyses can be performed using either effective or total stress. Duncan (1996) notes total stress analyses are valid for scenarios with critical short-term conditions. He recommended using an effective stress analysis when long term conditions are critical as total stress analyses do not consider the porewater pressure profile of the soil. Duncan (1996) showed that effective stress analyses use the Mohr-Coulomb failure criterion to describe the shear strength of the soil and can be extended to unsaturated soils using Eq. 4. For the purposes of research the software, SVSlope, has the capability to independently pick a method for calculating shear strength, a method of calculating slope stability and determining the critical slip surface.

In current practice the judgment of the designing engineer is used for the selection of the material parameters, and is a best estimate from laboratory or field test data. The accuracy of the factor of safety (FOS) is highly dependent on the accuracy of these parameters.

The limit equilibrium approach

Limit equilibrium analyses solve the problem from the assumption of force and/or moment equilibrium. Duncan (1996) states the factor of safety, F, is defined as the ratio of the shear strength of soil to the shear stress required for equilibrium. At the onset of failure the shear strength along the slip surface is assumed to be fully mobilised and the factor of safety is constant along the length of the entire surface. The factor of safety from the Morgenstern-Price method will be used for the purposes of this research as it is prone to the least amount of errors and is most suitable to the problem.

The finite element method (FEM)

Using the finite element method (FEM) of analysis is a numerical solution technique. It requires initial conditions, boundary conditions and the stress–strain properties of the soil. Tan & Sarma (2008) report that the FEM calculates the stress and deformation of the soil and interprets a slip surface from the regions of high strain. Griffiths & Lane (1999) show that the FEM is a more accurate model of the slope by not making several assumptions, such as the predetermination of the slip surface that the limit equilibrium methods make.

Griffiths & Marquez (2007) define the factor of safety as the ratio of the average shear strength of the soil to the average shear stress developed along the critical failure surface. The FEM uses the strength reduction technique by factoring the model parameters c and φ. The strength reduction factor is gradually increased until failure of the slope occurs, when the algorithm cannot find a stress redistribution to satisfy the global equilibrium and Mohr-Coulomb criterion, at this point the factor of safety is equal to the strength reduction factor.

Three-dimensional slope stability

Three-dimensional (3D) design is important because it is more realistic and leads to a better understanding of slope failure. The vast majority of slope stability analyses are performed in two dimensions (2D) under the assumption of plane strain conditions. In some cases of design practice 3D analyses are still not used when 2D conditions are inappropriate to model. Currently the accepted design approach for slope stability problems is to analyse the problem with "critical" values of two-dimensional (2D) geometry assumed to be constant over an infinite width. Griffiths and Marquez (2007) state the assumption this assumption is validated because the 2D solution is a conservative case, i.e. the three-dimensional (3D) solution would have a higher factor of safety.

Review of slippage in Murray Bridge

After a slippage occurred along the banks of the Murray River on the 4th of February 2009, Frazer (2009) reported on a preliminary investigation of the site, undertaken on 13th February 2009.

Historical data of river level height in Murray Bridge showed that the river level dropped approximately two metres over a two and a half year period between October 2006 and April 2009. The lowering of the river level aided evapotranspiration in drying out the soil however precipitation infiltrated the soil causing it to gain moisture.

Fredlund et al. (1993) reported that a change in the negative pore-water pressure profile associated with heavy rainfall is the cause of numerous slope failures. Failure has occurred on some sections along the riverbank and these failures appear to be associated with slumping and sliding of the soil mass along pre-existing failure planes and tension cracks. It is possible that failure along the pre-existing surfaces triggered by drying is a central mechanism in triggering failures as the river level drops.

Frazer (2009) reported that it appeared likely that a smaller secondary slip occurred prior to the main slippage. It was not until 4 days before the failure when a visible crack was reported approx 10mm wide x 20m long running parallel to the riverbank, in the approximate alignment of the future scarp. Tension cracks present throughout the soil mass prior to the slippages prevent shear resistance along the failure plane. According to Frazer (2009) the cracking is thought to have originated from the combination of consolidation and shrinkage of the clay above the lowered water level.

Summary of literature

Previous work from the School of Civil, Environmental and Mining Engineering at the University of Adelaide by Jones et al. (2009) illustrates that using two software packages of SVOffice can model the effects of transient seepage and slope stability. SVFlux, models the effect of climatic type events on soils and outputs the porewater pressure profile, this provides a good estimate of the actual state of soil saturation. SVSlope is capable of importing the porewater pressure profile and calculating shear strength based on unsaturated soil mechanics, the factor of safety can then be calculated using various methods of slope stability. The use of this method of analysis leads to the calculation of shear strength being more realistic which in turn leads to a more accurate model and a better understanding of slope failure.

4. DISCUSSION OF RESULTS

These results will examine the effect of a varying river level, geometry of the slope and climate conditions in relation to the dimensionless time parameter, T. The permeability of different types of clays is highly variable. Using a dimensionless time factor, T, allows the results to transcend to different types of clays with similar model parameters: c', φ', φ^b. The results will look at the variation of factor of safety with T. The time 't' is converted into 'T' using Equation 5

$$T = \frac{t k_{sat}}{H} \qquad (5)$$

Where: t is the elapsed time (days); k_{sat} is the saturated permeability of soil (m/day), and H is the height of river bank slope.

The effect of a varying river level

Figure 2 shows the results of Factor of safety (FOS) when there is a continuous drop in the river level until a time factor, T, when the river level remains constant. The results imply that the drop in FOS is more severe when the water level was lowered over smaller values of T. To maximise the FOS, T has to be maximised which is a product of permeability and time. This can be interpreted as soils with a low coefficient of permeability require a longer time to disperse the porewater pressures. A soil with a large coefficient of permeability requires less time to disperse porewater pressures. The instantaneous drop, (T=0) illustrates the rise in FOS, as T increases, due to the water table drying as an attempt to equilibrate with the river level. The same argument can be extended in Figure 3 for different magnitude drops in the river level.

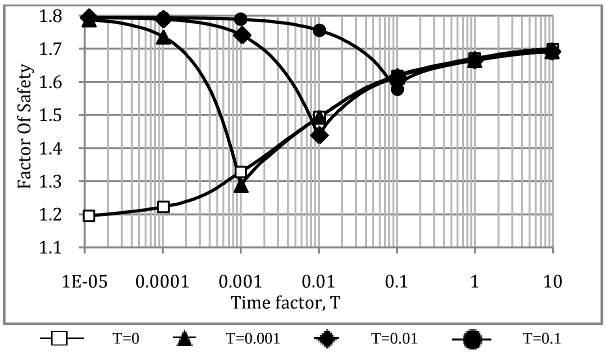

Figure 2 - 2m drop in river level over time period, T

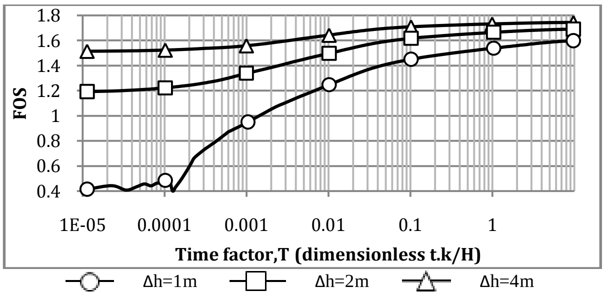

Figure 3 - Instantaneous drop in river level, Δh.

The results in Figure 4 show that the rise in FOS is more severe when the water was raised over smaller values of T. It is the opposite trend as discussed for the case of a drop in river level. This model does not have any negative repercussions on slope stability, the results show that when the water table rises with the river level it reaches a zero net flux state. The instantaneous rise sets a trend for a rise over any time factor as was the case for an instantaneous drop setting a trend for a drop over any time. Investigating different instantaneous water level rises gives an understanding of how the FOS changes with varied rises in water level over different time factors. Figure 5 shows the effect of raising the water instantaneously with respect to the magnitude of water level rise.

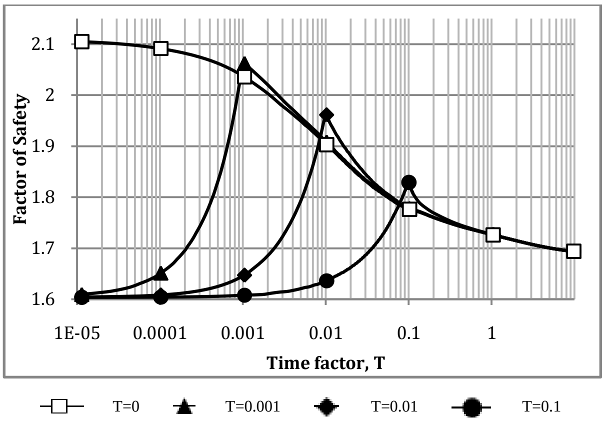

Figure 4 - 2m rise in river level over time period, T

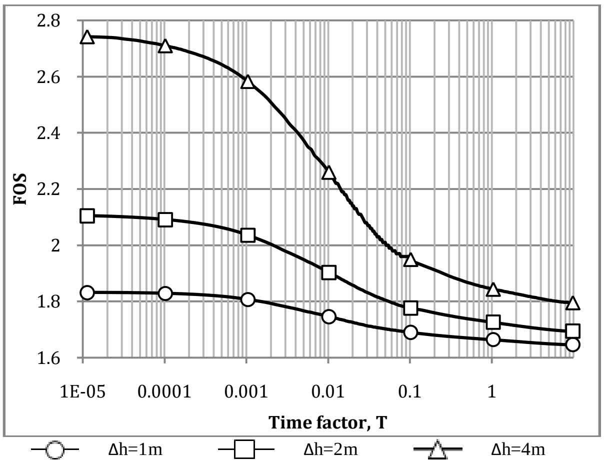

Figure 5 - Instantaneous rise in river level, Δh.

The effect of geometry

To ensure the results of modelling were as expected a study of geometry of the slope was undertaken. To examine the effect of the geometry of the slope on the slope stability six cases were modelled. These are summarised in Table 1. Although this only covers a small selection of possible slopes it was only intended by the authors as a suggestion to describe how the different geometry would change the factor of safety.

Table 1 - Cases for analysis of geometry

		β (°)		
		45	26.6	18.4
H (m)	10m	Case 1	Case 2	Case 3
	15m	Case 4	Case 5	Case 6

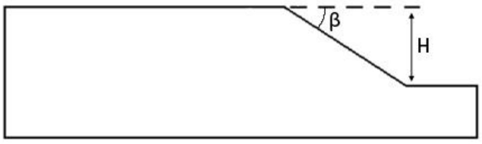

Figure 6 - Configuration of geometry analysis

A 2m instantaneous river level drop was applied to the model to investigate the combined effect of geometry and the change in head. Figure 7 shows that as the height of the slope was increased it will become more unstable and consequently the factor of safety will decrease. Similarly if the slope angle were to increase a decrease in FOS resulted as expected.

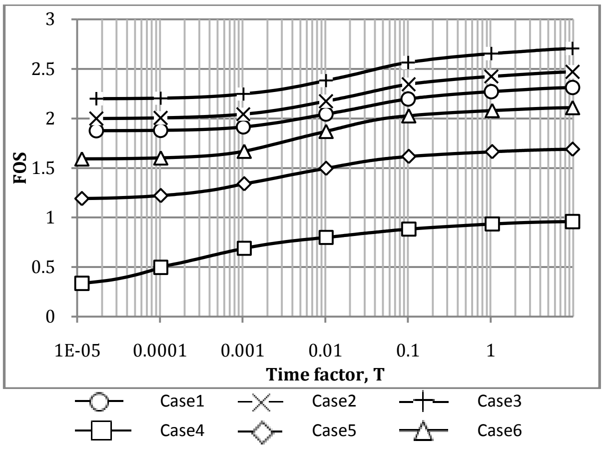

Figure 7 - Geometry analysis

The effect of climate conditions

Winter-type conditions will cause the water table to rise due to infiltration from precipitation and consequently the FOS will drop. Summer-type conditions will cause the water table to fall due to evapotranspiration and this will increase the FOS. Figure 8 shows a 90 day model with various river level and climate scenarios. Including the two most extreme situations, a river level drop in winter and a rise in summer. It can be interpreted that 'normal' climate conditions naturally help the water table oppose the change in river level. This opposition of change slightly dampens the effect on the FOS. This implies that river level conditions are dominant over climate effects.

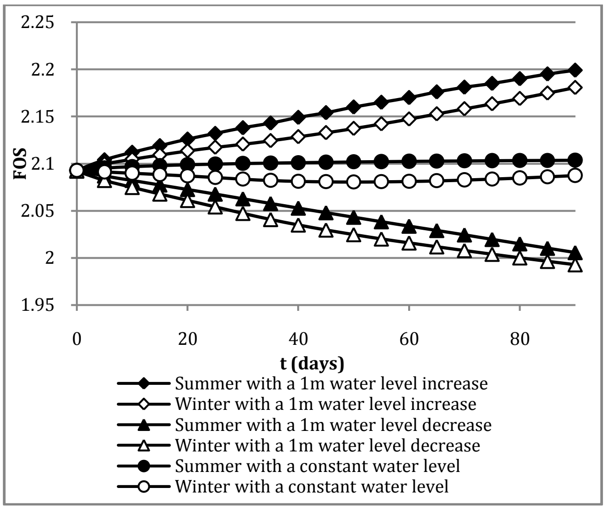

Figure 8 - Climate and water level scenarios

Murray Bridge case study

This section will look a case study in Murray Bridge. The soil profile is made up of two layers. The top layer is 8 metres deep and is silty clay with a low coefficient of permeability. The bottom layer is soft grey clay with an extremely low coefficient of permeability. Figure 9 shows the results of the factor of safety over time in days. The river level shows a direct influence on the FOS, whenever the river level drops the factor of safety also drops.

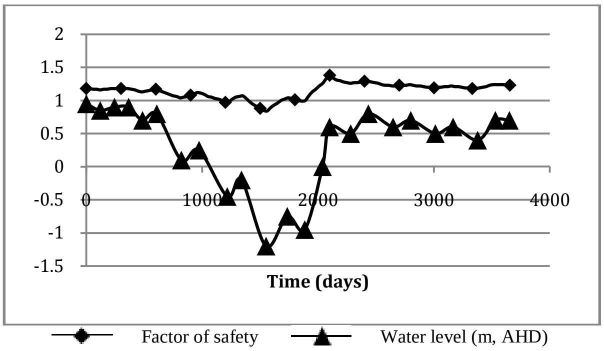

Figure 9 - Comparison of water level and FOS, vs. time

According to our research, using the homogenous soil, the factor of safety is expected to drop after a decline of the river level during summer however the effect is dampened by the seasonal drop of the water table due to the climatic effect of evapotranspiration, the drying of the soil. The drying of the soil allows soil suction contributes more to shear strength and in turn increases the force resisting failure. However, the porewater pressures in the bottom layer had not reduced after the water table had dropped with the river level due to the extremely low permeability of the soil. This factor contributed to the excessive nature of the drop in FOS as seen in Figure 2.

It was found using the initial porewater pressures associated with a -1.2m AHD water table, that the FOS calculated is 1.11 compared to 0.88 which was undertaken during the transient analysis. This steady-state analysis has validated our theory of low permeability causing the severe drop in factor of safety.

The effect of earthworks on slope stability

Two-dimensional (2D) analyses assume the cross sectional geometry is true for an infinite width. In the Murray Bridge case the material properties of the two soil layers are variable, but the physical dimensions of the riverbanks are very similar, with the levee bank extending parallel to the river for its entire width throughout the area. It can be assumed that the factor of safety is well represented using a 2D analysis.

After earthworks were completed to reduce the risk of slope failure according to a 2D analysis the excavated section could no longer be represented by a regular 2D analysis. Figure 10 shows that cross sections A & C have the 2D geometry of the unexcavated section and cross section B has the most optimistic 2D geometry however it is only valid for the excavated section not over an infinite width.

The authors suggest that the increase of the factor of safety of the cross section at B, due to the earthworks cannot be completely realised due to the nature of the 2D assumption over an infinite width. But in all likelihood the true factor of safety will lie somewhere in the range of analyses of cross sections A and B as shown in Figure 11.

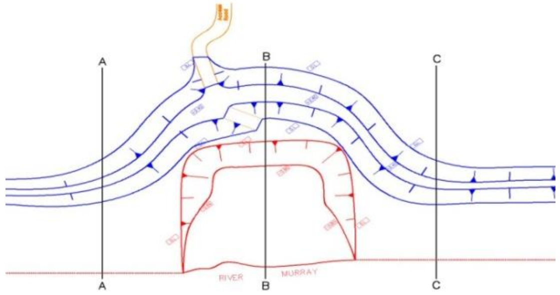

Figure 10 – Earthworks in Murray Bridge

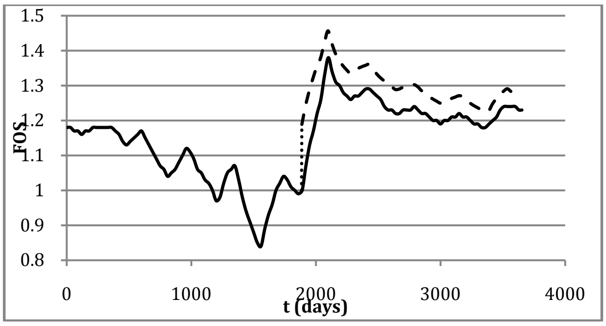

Figure 11 – Effect of earthworks on factor of safety

5. CONCLUSION

The research presented examines the effect of declining water levels on the stability of riverbank slopes. Where; climatic factors, geometry of the slope, material properties of the soil and time taken to vary water level all influenced the stability of the slope. Our research methodology led us to important results and the research outcomes are summarized below:

- The contribution of soil suction to shear strength was considered. However the influence of the unsaturated soil on shear strength was lessened by the presence of high groundwater tables;
- The lowering of the river level aided evapotranspiration in drying out the soil however precipitation infiltrated the soil causing the soil mass to gain moisture;
- Due to extremely low permeability of some soils, the porewater pressure profile does not change quickly with a change in water table depth. This was the cause for the large drop in the factor of safety at Murray Bridge.

The software package SVOffice, with its advanced numerical modelling techniques is emerging as a better way to undertake routine geotechnical analysis. The addition of SVSolid to the coupled analysis of seepage and slope stability modelling could be exciting as the improving FEM techniques can be compared against traditional limit equilibrium methods.

Using the method of unsaturated shear strength for design decreases the likelihood of a conservative solution it is important to ensure that the model parameters are accurate as this can lead to underestimated factors of safety.

6. ACKNOWLEDGEMENTS

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