Modelling the behaviour of unsaturated, saline clay for geotechnical design

Evan W Jones
School of Civil, Environmental and Mining Engineering, University of Adelaide

Yih H Koh
School of Civil, Environmental and Mining Engineering, University of Adelaide

Bradley J Tiver
School of Civil, Environmental and Mining Engineering, University of Adelaide

Marcus A H Wong
School of Civil, Environmental and Mining Engineering, University of Adelaide

Abstract
In recent times, there has been much discussion regarding the use of unsaturated soil mechanics for the design of earth retaining structures in Adelaide's semi-arid conditions. The soil-water characteristic curve (SWCC) is the main design tool within this field as a means to incorporate the additional shear strength associated with total soil suction. However, the majority of research to date only incorporates matric suction. This paper attempts to adopt the total suction profile to more effectively capture the behaviour of saline clays in Adelaide as osmotic suction is the dominant component of total suction. Furthermore, this research also considers clay soil behaviour, climatic effects over a 120 year period and identification of worst-case-scenarios in order to increase design efficiency. Previously published results were verified using the recently developed software SVOffice 2009, created by SoilVision Systems Ltd. and an analysis of the Millswood Underpass was conducted. This paper confirms the relationship of total soil suction to strength of Adelaide clay known to design practitioners yet still not used in design. These results will pave the way for further research in order to improve the way retaining structures are built on Adelaide clays.

1 Introduction

The majority of geotechnical design practice is currently based on saturated soil mechanics and effective stress analysis. Unsaturated soil mechanics, however, is slowly emerging as a means of optimising design. Recent advances in computing technology have lead to the ability to undertake long term analyses using complicated numerical models, allowing further research to be conducted in this field.

Expansive, or reactive, soils are often problematic, existing around much of metropolitan Adelaide. These soils expand and contract with changes in moisture content, with the potential to cause significant structural damage to lightly loaded structures. The unsaturated saline clays present in Adelaide are subject to these changes as a result of the varying seasonal conditions. It is this phenomenon that further complicates geotechnical engineering analyses, particularly for modelling the stability and movement of structures over long periods of time.

In recent years, there has been much discussion regarding the use of unsaturated soil mechanics for the design of earth retaining structures in Adelaide's semi-arid conditions. The Millswood Underpass, south of Adelaide, South Australia, is one such example and is the inspiration for this research, illustrating the strength of unsaturated clay soils as it has stood unsupported for 94 years. As a result, it is believed that the need for the extensive soil retaining features built into current designs is largely unnecessary.

2 Theory

Unsaturated soil mechanics is a field that combines soil science, fluid mechanics and soil mechanics. Clay behaviour depends heavily on the water content, and as such, it is important to understand water movement in unsaturated soils. Current methods to explain unsaturated flux are through the use of the soil-water characteristic curve (SWCC) and soil suction.

2.1 The soil-water characteristic curve

The gravimetric water content (W_w) versus matric suction (ψ_m) plot is known as the soil-water characteristic curve (SWCC), illustrated in Figure 1. As a result of the soil's affinity for water differing for each soil, the SWCC is a unique plot for each soil, effectively representing the unsaturated soils 'fingerprint'.

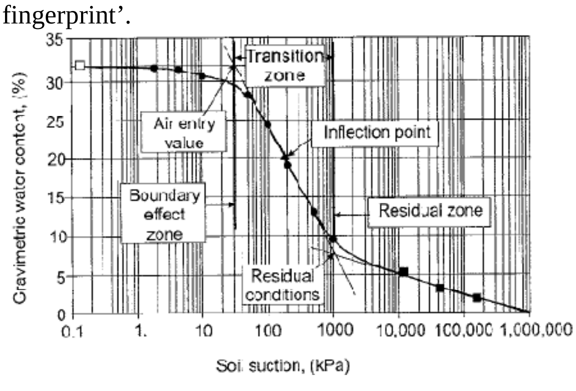

Figure 1: General soil-water characteristic curve structure (Fredlund, 2006)

A semi-empirical approach to fitting the SWCC incorporating the shape and pore-size distribution was proposed by Fredlund and Xing (1994), Eq. 1. Soil behaviour parameters a_f, n_f and m_f relate to the air entry value, the rate of water extraction once the air entry value has been exceeded, and the residual water content, respectively. A correction factor, C(ψ), Eq. 2, with parameter h_r, which represents the suction at which residual water content occurs, forces the gravimetric water content to zero at the maximum soil suction limit of 1,000,000 kPa (Leong and Rahardjo, 1997). This correction makes Eq. 1 more theoretically sound compared to its predecessors as suction values are unable to exceed 1,000,000 kPa according to thermodynamics.

The challenge is to adopt total suction rather than matric suction as used in Eq. 1 to more effectively capture the behaviour of saline clays in Adelaide, as osmotic suction represents approximately 80-90% of total suction (Peter, 1979).

$$W_w = C(\Psi)\left[\frac{1}{\left[ln\left[exp(1)+\left(\frac{\psi}{a_f}\right)^{n_f}\right]\right]^{m_f}}\right]W_s \qquad [1]$$

Where: $$C(\psi) = \left[1 - \frac{ln\left(1+\frac{\psi}{h_r}\right)}{ln\left(1+\frac{10^6}{h_r}\right)}\right] \qquad [2]$$

2.2 Slope stability in unsaturated soil

Slope stability analysis is an evaluation of risk, represented as a factor of safety against failure. In unsaturated soil, additional shear strength is gained through soil suction. Fredlund et al. (1978) proposed the following equation, Eq. 3, defining shear strength in terms of effective stress with an additional contribution by matric suction.

$$\tau = c' + \sigma'\tan\varphi' + \psi_m\tan\varphi^b \qquad [3]$$

τ=total shear strength (kPa); c'=effective cohesion (kPa); σ'=net normal stress minus the pore air pressure, $(\sigma_n\text{-}u_a)$ (kPa); φ'=effective friction angle (°); ψ_m=measured matric suction (kPa); and φ^b=contribution of matric suction to shear strength (°).

Adopting total suction in this instance also requires a new equation to be defined, Eq. 4.

$$\tau = c' + \sigma'\tan\varphi' + \psi_t\tan\varphi^{bt} \qquad [4]$$

ψ_t=measured total suction (kPa); and φ^{bt} =contribution of total suction to shear strength (°).

There are many available methods for analysing slope stability. The method used in this research is the Morgenstern-Price method. This method satisfies both moment equilibrium and horizontal force equilibrium for the sliding mass. The interslice forces were improved to be functions such as half-sine or trapezoid functions. The solution involves an integration method based on the Newton-Raphson technique (Feng, 2008).

3 Methodology of research

The two computer programs made available for the purpose of this research were SVFlux and SVSlope, part of the SoilVision Systems Ltd. software package SVOffice 2009. These two programs were capable of bridging the gap between saturated and unsaturated soil mechanics; an area that had not been previously accomplished.

The methodology adopted for this research sequentially increased in complexity required to achieve the final results. The outputs from SVOffice 2009 were verified against literature published by Xiong (2007) and Ward (2009) and the Morgenstern-Price method was definitively chosen from a choice among multiple solution methods.

3.1 Formation of climatic and soil parameters

Until recently, the ability to incorporate long periods of climate data into transient numerical analysis has been unfeasible, due to software limitations and computational capabilities. As climatic influences were seen as an imperative factor in modelling unsaturated slope stability, they could no longer be over looked. As such, initial stages of this research involved de-aggregating the last 120 years of climate data for Adelaide, courtesy of the Bureau of Meteorology of Australia. A number of steps were required in the reduction of the climate data before it could be used effectively. A balance between rainfall and potential evaporation was calculated to determine if the soil would be wetting or drying, this was used for determining the time steps for SVFlux inputs. This reduced the number of time steps from 1440 to 320 to increase the efficiency of the modelling.

A fundamental difference between this and previous research is the use of total suction, rather than matric suction, for the analysis of slope stability. As such, there was very little data available for the formation of total suction SWCCs for saline clays. It was therefore determined that developing a new method to estimate an SWCC was the optimal way of proceeding with this research, as the resources and time for laboratory testing was not a feasible option. What was available was a known total suction profile and climate records for Adelaide, a saturated volumetric water content (VWC) estimate for Keswick Clay, and the software SVFlux. A minimum of 15 data points were used to estimate a total suction SWCC whereby a Fredlund and Xing (1994) fit was applied. This soil was then tested in a 9m deep, 6m wide soil profile with a climate boundary along the surface and the numerical model was run for a period of 30 years. The moisture flux and porewater pressures were then monitored and modifications made to the soil until a suction range, depth of influence and equilibrium pressure were matched to the design profile. Minor modifications were made to the hydraulic conductivity function for the soil to 'fine tune' the soil behaviour parameters. The result of this procedure is a new method for determining the SWCC using numerical techniques and a theoretical soil representing Keswick Clay for research purposes.

3.2 The response of Keswick Clay to the addition of water

The aim of this research was to better understand the response of unsaturated clay upon the addition of water and how this relates to a slopes factor of safety. The effect of three distinct moisture sources were examined;

- The presence of a groundwater table;
- The event of a flood; and
- Impacts due to leaking services.

It is well understood that all of these influence the factor of safety, yet is only now that the computational ability to perform the necessary calculations is emerging.

The presence of a groundwater table is a common occurrence in many design situations where excavations are involved. This investigation was aimed at determining the depth at which a groundwater table affects a slopes stability and whether having impermeable barriers helps to increase the factor of safety. In Adelaide there are two common groundwater table depths, 8m and 15m. Two other scenarios were also considered where the groundwater table is at the toe of the slope and a non-existent groundwater table. These groundwater table depths were then conducted on three different slope exposures as seen in Figure 2 using the slope geometry of Millswood Underpass.

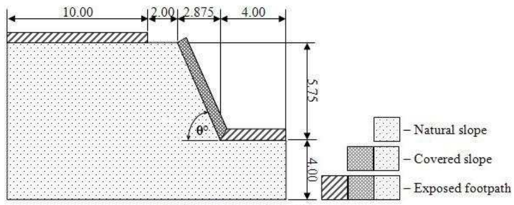

Figure 2: Different slope exposures investigation

A major concern in adopting unsaturated soil mechanics into geotechnical design are the unknown effects of extreme events such as flooding, leaking or burst services. Of great importance is knowing the duration of time that such events require to cause failure.

Flooding was investigated using an unprotected slope based upon the geometry of Millswood Underpass. Initially, models were run without the incorporation of climatic data. The flood was represented using a head expression formed through the use of logic expressions, represented in Figure 3. This allowed for the soil to reach equilibrium prior to the flood being initiated, upon which the slope remained flooded until the factor of safety stabilised. The flood then subsided allowing the factor of safety to return and the recovery period determined.

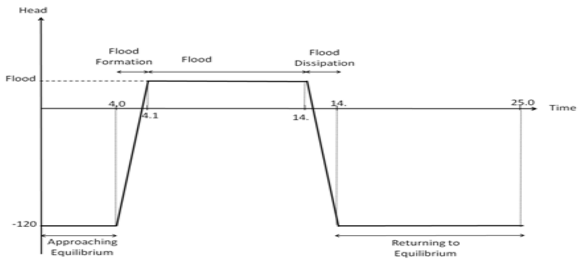

Figure 3: Flooding function used in SVFlux

This process was run at flood levels ranging between zero and 2m at 0.25m intervals, as well as at 5.75m (the height of Millswood Underpass). Further modelling was then done incorporating the effects of climate over a 50 year duration, with the flood being initiated during the wettest period to model the potential impacts given more realistic conditions.

The aim of modelling a leaking service was to assess the effect of a ruptured water source beneath the surface on the profile. Major issues arise from leaking services as the problem can exist unnoticed for extended periods of time and therefore it is essential to assess its effect on a soil profile and understand the response to the additional moisture. The modelling technique adopted for this scenario involved positioning a 'source' at a depth of 2.75m below the ground surface and a distance of 6.00m from the face of the slope. The flow rate for the leaking service was $8.64m^3$/day, whereas for the burst pipe this was increased to $172.8m^3$/day. Upon initiating the onset of the leaking service it was allowed to continue for the duration of the model, while the burst pipe was allowed to run for five days. These time periods allowed for the inclusion of moisture to cause the maximum damage to the slope.

It should also be noted that many problems arose during the use of SVFlux and SVSlope. Using such advanced software with its ability to incorporate such a detailed field as unsaturated soil mechanics, meant that some programming errors halted our progress at various stages. Regular contact was required with the staff at SoilVision Systems Ltd. and together these problems were resolved.

3.3 Assumptions made for modelling purposes

The assumptions made in this research are a homogenous soil profile, with no structural defects such as slickensides and perched water tables. There was also no consideration of loading conditions.

4 Results and discussion

The results produced in our research showcase the potential that emerging, sophisticated software packages have on geotechnical engineering, research and design. The ability to incorporate climatic influences and moisture flux permitted the formation of a new SWCC estimation technique as well as monitoring the effects that groundwater tables, flooding and leaking services have on the stability of a slope.

4.1 Results from a numerical technique to determine an SWCC for Keswick Clay

The ability to use climate data as a means to estimate an SWCC is an approach only made available through the computational power of software such as SVFlux. This method replaces the requirements of arduous, expensive laboratory testing for first approximation during a design process. The final curve fitted for the approximation of Keswick Clay is shown in Figure 4.

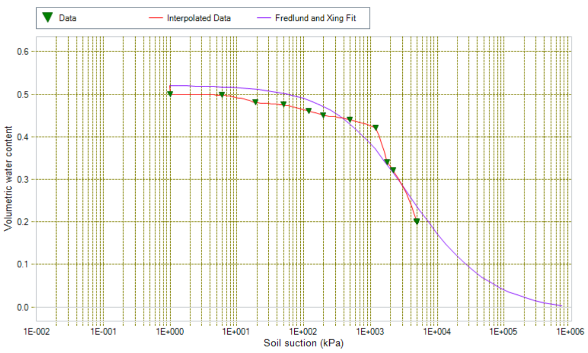

Figure 4: Keswick Clay SWCC showing data points and fitted Fredlund and Xing (1994) equation

Figure 5 shows a number of suction profiles from the transient analysis run over 30 years using the soil-water characteristic curve described above. The result of running the model for 30 years at 0.2 year increments is a suction range between 400 kPa and 3000 kPa at the surface. This variation does not quite capture the range of suction experienced in Adelaide but the range of results for the intermediate years is weighted to the lower side of the equilibrium state experienced in Adelaide. The result of this is that the additional shear strength as a result of soil suction is conservative, therefore not overestimating the factor of safety of slopes using this soil.

The flux profiles suggest that at 4m below the surface there is a fluctuation of ±200 kPa from the design profile, however, beyond 6m the suction remains constant at *pF* 4.2. However, this has never been proven and is based upon field observations. This minimal variation is further validation that the data adopted for use in this research is representative of Keswick Clay.

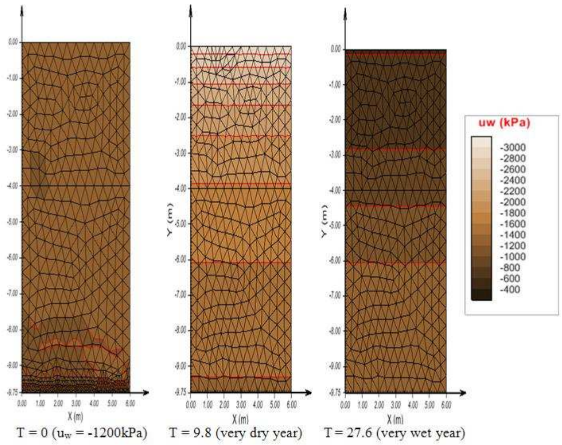

Figure 5: Changing suction profiles showing the depth of influence for Keswick Clay SWCC

4.2 The effects a groundwater table has on slope stability

The investigation into groundwater table effects on slope stability uncovered a number of trends relevant to geotechnical design. It was found, although quite intuitive, that for a given groundwater table the factor safety increases as the degree of exposure decreases, seen in Figure 6. However, it was the rate of change and the explanation that is of use in design practice. It was found that when a groundwater table is within 8m of the surface, the moisture in the soil profile is dominated by moisture originating from the groundwater table. Therefore, the inclusions of moisture barriers, under these circumstances, do not cause any significant increase in the factor of safety of a slope and the use conventional design techniques are recommended. On the other hand, when a groundwater table is beyond 8m of the surface, the moisture in the soil profile is dominated by climatically induced moisture. Under these circumstances the prevention of water into the profile significantly increases the stability of the slope and construction methods can be modified to incorporate the additional strength.

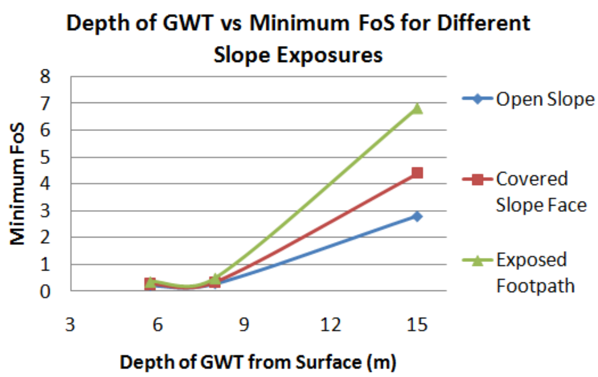

Figure 6: Depth of groundwater table versus minimum factor of safety for an open slope, covered slope face and exposed footpath

4.3 Flooding effects

The results of the impacts of flooding detailed the duration required for an open slope to reach, and return from, a minimum factor of safety, as well as stability reduction. These were calculated from the factor or safety versus time plots such as in Figure 7. In general, it was found that a slope's factor of safety would continue to reduce for a period of 4.5 years, however over half of the reduction was lost in the first time period of 0.2 years. The recovery period for all flood heights exceeded the reduction duration by approximately one year.

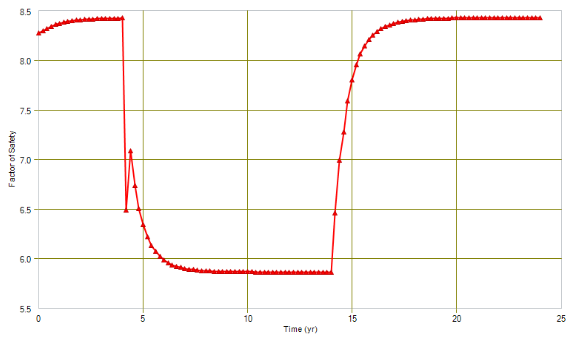

Figure 7: Change in factor of safety over 25 years for a flood condition at Millswood Underpass for a 0.25m flood

The complexity of the model was increased by the incorporation of climate data along the exposed boundaries rather than a constant head of -120m. This allowed the soil profile to undergo seasonal variation. In the previous scenario, the influence due to the flood was not enough to cause failure, however with the incorporation of climate the results were notably different, seen in Figure 8.

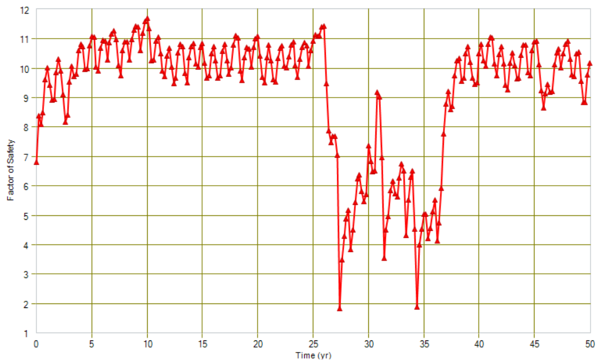

Figure 8: Change in factor of safety over 50 years for a 0.25m flood incorporating climatic data

It was found that floods exceeding 1.00m in depth had the potential to cause failure, with floods exceeding 1.50m causing extreme risk. The method of failure involved the top of the slope 'crumbling' rather than a mass movement of the slope as seen in the previous investigation. This can be seen as evidence that for an accurate analysis of slope stability under flooded conditions, incorporating both the influence of the flood as well as seasonal variations is required.

4.4 Leaking services

The first analysis for a leaking service examined the effect of a slow leaking pipe. As can be seen in Figure 9, despite the constant influx of water inside the soil profile, the factor of safety never falls below 1.70, reaching a steady state after 120 days. This demonstrates the high strength nature of Keswick Clay, and the large window of opportunity for maintenance of the pipe. This also indicates that even if a leaking service remains undetected for a long period of time, there would be little adverse effects.

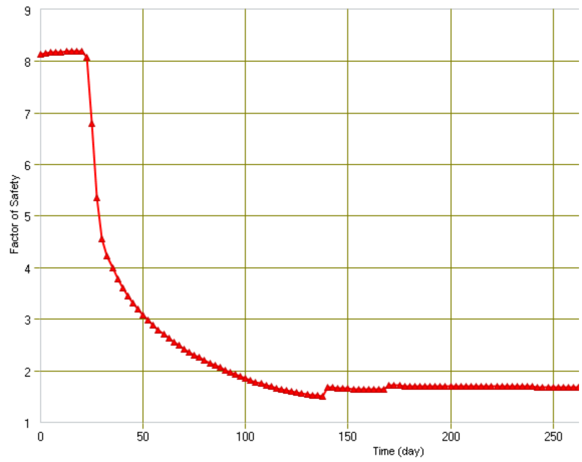

Figure 9: Change in factor of safety for a slow leaking service over 250 days

The explanation for this is that for a small, consistent flow rate, the porewater pressure reaches steady state before a critical saturation level is reached. However, since the program available could not analyse volume change, erosion surrounding the location of the leak was not assessed. This phenomenon will occur in the field so, in reality, if the leak continues unnoticed this situation will eventually lead to a burst pipe situation and this is discussed below. Furthermore, it is important to note that these results were for constant equilibrium environmental conditions; hence fluctuations in moisture flux within the soil as a result of climatic conditions were not assessed. These fluctuations would likely affect the factor of safety on an open slope. For example, if the leak occurred in summer, the factor of safety would increase, and more importantly, when assessing slope stability, a decrease would occur for a leak in winter.

The second analysis investigated the effect of a ruptured water main and a much different result was obtained. As can be seen in Figure 10, when the pipe bursts on day 30, a steep decline in the factor of safety occurs that coincides with a steep increase in the porewater pressures in the soil.

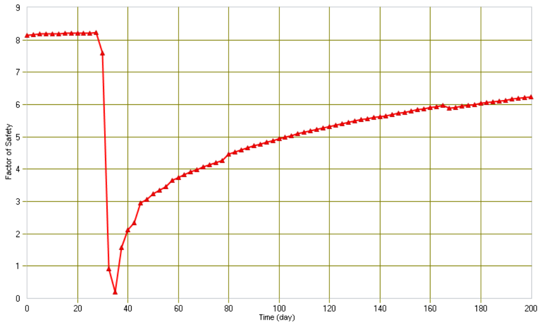

Figure 10: Change in factor of safety for an underground burst pipe over 200 days

Crucially, the factor of safety falls to 0.17 five days after the burst, well below the critical value of 1.25 and failure of the slope occurs, highlighting the importance of designing against this occurrence. However, it should be noted that after failure, the factor of safety begins to recover; in reality the slope has already undergone catastrophic failure so there would be no such recovery. This is a limitation of this program that would be resolved by using the volume change software SVSolid. Despite this, the results demonstrate that maintenance checks should occur on any services within a slope profile to ensure against a pipe burst.

5. Conclusions

This research investigated the long term climatic influences on slope stability in unsaturated saline clay, such as those commonly found in the semi-arid climate of Adelaide, South Australia. Many factors were assessed, including soil behaviour, climatic effects and worst-case-scenarios leading to slope instability. The outcomes from this research will be applicable for the purpose of increasing overall efficiency in revetment design. The research outcomes are summarised below.

An SWCC for Adelaide's Keswick Clay was calibrated using the available climate data. This had never been done before and the incorporation of Adelaide's climate data into flux models to validate the SWCC against field-based suction values should be seen as a significant achievement in this area of research.

A deep groundwater table of 15m will allow excavation to reach 5.75m without support, whereas for a shallow groundwater table a staged excavation is recommended.

Flooding at the Millswood Underpass to a depth of 0.25m above the road surface at the toe of the slope is unlikely to cause failure with the incorporation of other climatic influences. Even a depth of 1.00m has a factor of safety of 1.20, highlighting the strength of unsaturated saline clay.

Under controlled environmental equilibrium conditions, such that there were no flux boundaries available at the Millswood Underpass, a slow leaking service did not cause failure of the slope. A burst pipe, however, caused ultimate failure of the slope and highlighted the need for regular maintenance checks.

6. Closing remarks

Due to the complexity and infancy of this software there exists the potential for some error as SoilVision Systems Ltd. made it aware to the authors that a small error was found when coupling the two programs used for this analysis.

The future of research in this field is exciting and ever expanding with the development of more powerful computers and software packages, such as SVFlux and SVSlope. With the involvement of computing techniques, this field of geotechnical engineering, research and design will proceed in leaps and bounds.

7. Acknowledgments

This research was carried out with the assistance and guidance of Dr. William Kaggwa whom the authors would like to sincerely thank. His patience and understanding was much appreciated.

8. References

Feng, T. (2008), *SVSlope Theory Manual*, SoilVision Systems Ltd, Canada

Fredlund, D.G. (2006), "Unsaturated soil mechanics in engineering practice", *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 132, no. 3, 286-321

Fredlund, D.G., Morgenstern N.R. & Widger, R.A. (1978), "Shear strength of unsaturated soils", *Canadian Geotechnical Journal*, vol 15, no. 3, 313-321

Fredlund, D.G. & Xing, A. (1994), "Equations for the soil-water characteristic curve", *Canadian Geotechnical Journal*, vol. 31, no. 4, 521-532

Leong, E.C. & Rahardjo, H. (1997), "Review of soil-water characteristic curve equations", *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 123, no. 12, 1106-1117

Peter, P. (1979), "Soil Moisture Suction", *Footings and Foundations for Small Buildings in Arid Climates*, Institution of Engineers, Australia S.A. Division and the University of Adelaide, Adelaide, June, 46-62

Ward, C. (2009), "Slope Stability Analysis – Unsaturated Soil", *Parsons Brinckerhoff Australia*

Xiong, Y.I. (2007), "Preliminary design of a facing wall for an underpass in unsaturated clays", *Geotechnical Group at the Department for Environment, Energy and Infrastructure*, South Australia