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Incorporation of the stabilising effects of soil suction in railway embankments

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ABSTRACT: Mine subsidence assessment considers the potential impacts of underground mining on infrastructure and natural features. It is generally necessary, therefore, to understand the pre-existing condition of infrastructure in order to undertake this assessment. Recently a number of railway embankments required such an assessment due to proposed longwalls adjacent to and in some cases directly beneath them. These embankments comprised loosely compacted sandstone and shale fragments, with slopes up to 40° from the horizontal. When analysed by standard stability methods these embankments show factors of safety below 1 belying their 100 year old existence. It was postulated that soil suction was the cause of continued stability but no readily established method was available to incorporate these effects. This paper documents the development of a method to conservatively apply soil suction in such cases without the need for extensive laboratory testing. Subsequently four embankments were instrumented to verify that the expected suctions exist and that they are unaffected by climatic changes. Methods and test results are detailed in the paper. This method was subsequently accepted by the Department of Planning and the Environment as part of mining approvals. It is expected that this method may be applied to other embankments where there is a need to include the effects of soil suction on slope stability.

1 INTRODUCTION

Soil suction is a phenomenon which is well known and often explained as being the principle driver behind shrink-swell phenomena, surface cracking, greater than expected stability in soil slopes and high strength of desiccated clays. Application of this principle in geomechanics, however, is limited. This is largely due to the phenomenon being either seemingly too difficult to quantify, unreliable or poorly understood.

There are many cases, however, where the effects of soil suction have been integrated into mainstream scientific application. These include shrink-swell behaviour, water availability in agriculture and multiphase flow in porous media.

2 BACKGROUND

2.1 *Mining impacts on railway embankments*

Australia has been constructing and extending railways since 1830. Currently there is around 33,000 kilometers of track on three major track gauges. Much of the original single-track network has been retained and extended with upgrades such as widening. Many of these networks overlie coal reserves such as the Main Northern Line (MNR) to the north of Sydney and the Main Southern Line (MSR) to the south.

The MSR effectively stretches from Granville to Albury on the NSW/Victorian border. The first section of the MSR was a single line extension from Granville to Liverpool constructed in 1856. The MSR was later extended to Campbelltown in 1858, Picton in 1868 and to Goulburn in 1869. In the 1920s the embankments and cuttings were widened to accommodate line duplication. Then, in the 1980s further widening was undertaken to accommodate service roads on at least one side but generally both sides of the rail tracks. A typical embankment section is shown in Figure 1.

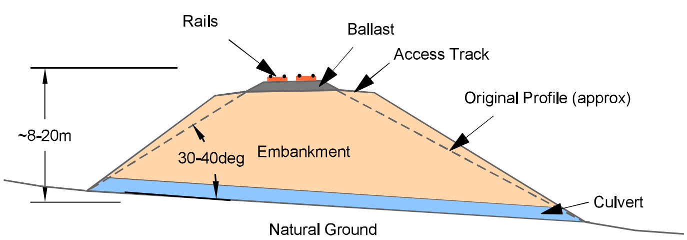

Figure 1. Typical rail embankment section

Given the MSR's age and location it is not surprising that it traverses over a number of active coal mining leases. Consequently, the assessment of potential impacts of mine subsidence on the railway system has been an on-going area of research, assessment, planning and execution.

Recently a number of railway embankments across several mine leases have been exposed to potential mining impacts. To obtain approval miners must establish that any such impact will not impede the general function of the rail line including embankments. This is normally achieved by first establishing the current margin of safety against failure or loss of serviceability and how this may change under predicted mining movement. In this case, however, widening of the embankments for duplication and services was undertaken predominantly at the crest, resulting in over steepened batter angles typically around 36 degrees and sometimes up to 40 degrees.

The embankment material comprises typically ripped sandstones and shales won from adjacent cuttings and placed by end tipping with uncontrolled compaction. Unsurprisingly, strength parameters inferred or even measured for this material suggest modest friction angles of 30 to 33 degrees and cohesions of only a few kPa.

2.2 *Shortcomings in stability theory*

Given embankment batter angles of 36 degrees and greater, friction angles of 33 degrees or less and very little cohesion, it is not difficult to anticipate that traditional slope stability analyses will predict that these embankments should not exist. However, their continued existence for over 150 years and in some cases, survival through high seismic and flood loading, casts doubt on the ability of traditional soil mechanics to adequately capture the current state of stability of these structures.

In most cases such deficiencies in theory, where known to be conservative, may be accepted and considered by the designer as acceptable as it errs on the side of caution. In this case, however, the current condition of these embankments cannot be reliably analysed using traditional stability theory and therefore the potential impacts due to mine subsidence cannot be assessed. This analysis deficiency needs to be understood and overcome to facilitate a reliable and effective assessment.

2.3 *Recognition of soil suction effects*

PSM, as well as other geotechnical engineers involved on the project and independent reviewers, established early on in the assessment process that the beneficial effects of soil suction within the embankment was the most likely cause of the discrepancy between theory and observation. This observation was based on previous investigations in which the embankment material was found to be relatively dry over the full height, well consolidated, contain a relatively high amount of clay based material and support relatively high vertical faces when excavated.

These observations have long been linked to the beneficial effects of soil suction in slope stability. Pioneering work in this area began in Hong Kong in the 1980s where very high steep slopes could not be explained by traditional soil mechanics and were found to be very susceptible to rainfall (Ching *et al.* (1984); Fredlund (1987)). Subsequent research was undertaken to extend the effective stress relationship to incorporate soil suction as described in Rahardjo *et al.* (1991); Ng and Pang (2000); Fourie (2016). The beneficial aspect of negative pore pressure on slope stability is shown schematically in Figure 2. More discussion on these approaches is provided in Section 3.

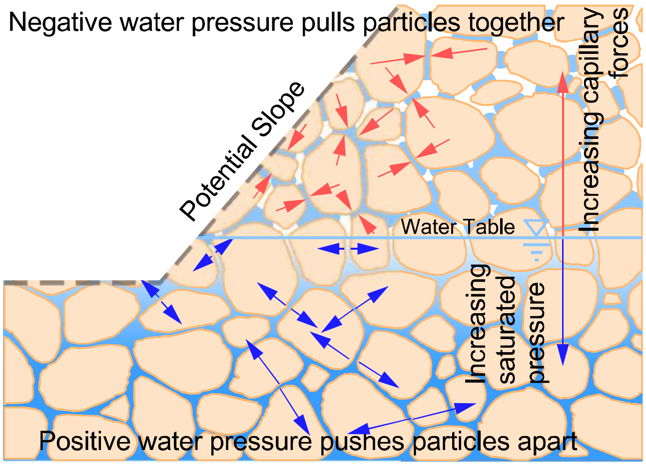

Figure 2. Stabilising forces of negative pore pressure

3 SOIL SUCTION, EFFECTIVE STRESS AND SOIL STRENGTH

3.1 *General*

The consideration of soil suction in slope stability analyses requires the following:

- An understanding of the magnitude and distribution of soil suction within the embankment
- Modification of effective stress to incorporate soil suction
- Use of modified effective stress in shear strength

These elements are expanded on below.

3.2 *Magnitude and distribution of soil suction*

Soil suction occurs in all unsaturated porous media. It is a measure of the differential between pore gas pressure and surface tension of water within pore spaces. A dominance of gas pore pressure, u_a, over liquid pore pressure, u_w, will promote the expulsion of water which is resisted by capillarity. Soil suction represents the force within the liquid (water) and consequently often referred to as 'negative pore pressure' as it is commonly measured relative to atmospheric pressure. The most common drivers for change in soil suction are gravity drainage and evapotranspiration.

As the gas-liquid pressure difference $(u_a - u_w)$ increases it is balanced by increased surface tension effects as water retreats into ever tightening pore spaces and vice-versa. This gas-liquid pressure difference is usually termed capillary pressure or matric suction. There may be additional osmotic effects related to changes in solute concentration across the liquid which contribute to overall 'total' suction.

For the most part the liquid system in unsaturated soils remains connected and therefore a continua as shown in Figure 2. Even at relatively high soil suction water will remain a thin film through which pressure changes are transmitted and flow initiated. This is why a lowered water table can initiate drainage of water from upper regions or evaporation can draw water from lower regions.

Under equilibrium conditions (no flow) pore water pressures are known to be hydrostatic – i.e. a meter increase in pore water pressure for every metre increase in depth below water table. This relationship also exists above the water table due to water continuity – i.e. a metre decrease in pore water pressure for every metre decrease in height above the water table.

This means that under hydrostatic conditions the distribution of soil suction in terms of capillary pressure is determined by location, z (in RL), and the vertical location of the water table (above or below), h_{wt} (in RL), and the unit weight of water, γ_w:

$$(u_w - u_a) = (h_{wt} - z)\gamma_w \quad (1)$$

For sloping water tables this may not strictly apply but in most cases it is sufficiently accurate enough to describe the distribution of positive and negative pore pressure within a body of soil, such as an embankment, at equilibrium.

Under transient conditions negative pore pressure distribution will be influenced by infiltration and evapotranspiration as shown in Figure 3.

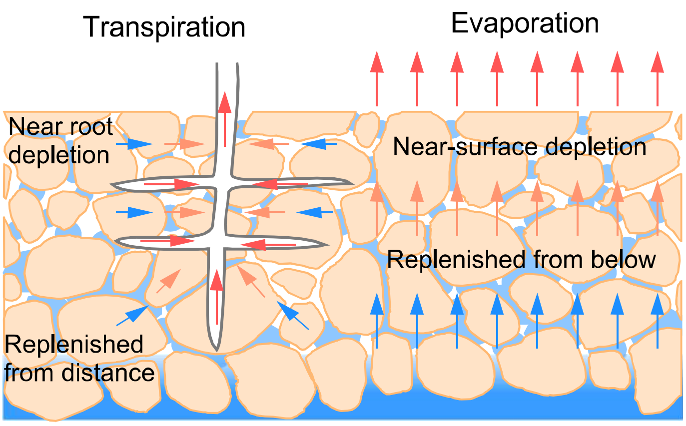

Figure 3. Connected water within the unsaturated zone.

3.3 *Incorporating Soil Suction into Effective Stress*

It is well established in saturated soils that shear strength is directly related to effective stress. It is desirable, therefore, to establish how soil suction might be incorporated into effective stress calculations as this would allow existing theories of volume change and strength to incorporate the effects of soil suction. This is expanded on as follows.
Effective stress under saturated conditions is given as:

$$\sigma' = (\sigma - u_a) - (u_w - u_a) \quad (2)$$

Where σ' is effective stress, σ is total stress, u_w is pore water pressure and u_a is pore air pressure. In many cases u_a can be assumed to be constant throughout the soil and at, or close, to atmospheric pressure. Importantly Equation 2 is based on average stress independent of the contact area.

Application of this relationship under negative pore pressure conditions would mean that increasing soil suction would result in increasing effective stress. This effect is widely recognised both theoretically and intuitively with both strength gain and volume reduction as soils dry out (i.e. corresponding to an increase in soil suction).

Bishop (1959) recognised that there was a diminishing contribution of soil suction to effective stress as a soil became more unsaturated proposing the following relationship:

$$\sigma' = (\sigma - u_a) - \chi(u_w - u_a) \quad (3)$$

Where χ equals one while the soil remains saturated but reduces towards zero as the soil desaturates. The χ parameter is usually found by back analysis of laboratory testing under controlled stress, pore pressure and saturation.

In the 1970s and 1980s Fredlund *et al.* (1978); Fredlund (1987) and others suggested a change to the Bishop (1959) formulation to account the effects of unloading. This led to recommendations by Fredlund (1987) that an additional parameter, χ_a was required to properly incorporate soil suction into effective stress and therefore shear strength calculations.

Subsequent research by Khalili and Khabbaz (1995); Khalili *et al.* (2004) and others showed that unloading effects could be more readily explained by including soil suction as a pre-consolidation. This re-established the Bishop (1959) relationship which is currently the most widely accepted method of estimating the effect of soil suction on effective stress.

To further improve the usefulness of the Bishop (1959) relationship Khalili and Khabbaz (1998) studied the χ parameters for 14 published studies around the world. From this analysis they proposed the following generic relationship for χ for any soil:

$$\chi = \begin{cases} \left[\frac{(u_a - u_w)}{AEV}\right]^{-0.55} & , u_a - u_w > AEV \\ 1 & , u_a - u_w \leq AEV \end{cases} \quad (4)$$

Where the Air Entry Value (AEV) is the level of negative pore pressure below which air will begin to enter a soil's pore space. It is also the level at which a soil can remain saturated above a water against gravity. The exponent value of -0.55 in Eqn 4 provided a good fit to the 14 published studies. This relationship is commonly used to link effective stress to soil suction in unsaturated soils.

The AEV is generally derived from stress and pressure-controlled laboratory apparatus. It is known to be unique to a soil pore space distribution, density and wetting path. More recently the effect of these factors on the AEV has been studied to further improve the understanding of these properties and reduce the demands of lab testing for a soil at different densities (Pasha *et al.* (2016); Pasha *et al.* (2017)).

3.4 *Soil suction and shear strength*

It has been established that shear strength, τ, is directly controlled by effective stress, σ', and the most widely used relationship relating these is the Mohr-Coulomb shear strength equation, this being:

$$\tau = \sigma' \tan\phi' + c \quad (5)$$

Using the more recent work undertaken by Bishop (1959); Khalili and Khabbaz (1995); Khalili *et al.* (2004) it follows that:

$$\tau = [(\sigma - u_a) - \chi(u_w - u_a)] \tan\phi' + c \quad (6)$$

If it is assumed that u_a is constant and other stresses are measured relative to it then:

$$\tau = (\sigma - \chi u_w) \tan\phi' + c \quad (7)$$

This can be expanded further by utilising Equation 4 which gives:

$$\tau = c + \sigma \tan\phi' - \begin{cases} \frac{u_w}{(|u_w|)^{0.55}} AEV^{0.55} \tan\phi' , & u_w < -AEV \\ u_w \tan\phi' , & u_w \geq -AEV \end{cases} \quad (8)$$

This relationship allows shear strength to be calculated under both saturated and unsaturated conditions. Shear strength is derived from strength parameters by knowing the AEV and the distribution of negative pore pressure.

4 APPLICATION OF SOIL SUCTION TO EMBANKMENT STABILITY ASSESSMENT

4.1 *General*

The inclusion of soil suction effects is recognized as potentially intransient. A reduction in pore water pressure due to rising water levels or infiltration may significantly reduce soil suction reducing strength. These effects are often used to explain how rainfall can cause slope failures even where fully saturated conditions do not occur. For this study pore water pressure conditions within the railway embankments under consideration are unlikely to change significantly because:

- The embankments sit proud of the natural ground level and are shaped to shed directly intercepted rainfall;
- The accumulation of floodwater adjacent to the embankment is minimised through the use of engineered culverts and other stormwater diversion structures; and
- The clayey embankment materials inhibit other than minor infiltration into the body of the free-standing embankments.

For one embankment in this study this hypothesis was recently directly tested during a 1 in 200 AEP flooding event that completely engulfed the embankment for a period of about 6 hrs. During this time piezometers installed in the embankment showed little to no change in pore water pressure.

4.2 *Adopted methodology*

Equation 8 can be used to include the effects of soil suction in shear strength and therefore stability calculations. Application, however, is contingent on knowledge of the AEV and soil suction distribution including infiltration and evaporation effects. Furthermore caution needs to be exercised in applying soil suction in this manner due to this being a relatively novel technique.

Taking into consideration these factors Equation 8 was conservatively applied to stability analyses for four existing railway embankments by the following approach:

- The soil suction distribution was assumed to largely follow Equation 1 except for the outer 1 m of material as per Figure 4.
- A relatively low value of AEV of 25 kPa was adopted based on published literature and groundwater table observations.
- The beneficial effect of soil suction used in Equation 8 was limited to the AEV.

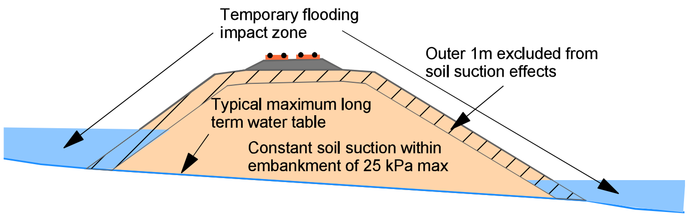

Figure 4. Application of soil suction within an embankment.

Limiting soil suction to the AEV provided these benefits:

- Higher (increasingly negative) and more variable soil suction (i.e. soil suction derived from being well above the water table) were not relied upon.

– The value for χ was always 1 as soil suction never was limited to increase above the AEV which simplifies the application of Equation 8.

These assumptions are assessed to be conservative because Equation 8 demonstrates that there is always an increase in shear strength with increasing soil suction.

Stability calculations have not been included here due to editorial constraints. In general the inclusion of soil suction effects as described here resulted in an increase in factor of safety of around 0.2 to 0.3 for the embankments under assessment. The incorporation of soil suction effects can be readily achieved in existing stability analysis packages, some of which can utilise negative pore pressure directly while others require customised user parameter fields.

5 VALIDATION

Rigorous validation of this method would require failure of a trial slope which was beyond the scope of this study. Instead validation was limited to demonstration of the presence and magnitude of soil suction.

Soil suction was measured through the use of soil tensiometers. Tensiometers were invented by the American soil physicist Wilford Gardner in 1912. They are a sealed column of water connected to a porous ceramic tip. When the ceramic tip is buried in the soil it acts as a membrane allowing the column of water to come into equilibrium with the soil suction at the tip. The column of water is connected to a pressure sensor which provides a reading.

Tensiometer have been used extensively in agriculture for nearly a century as they provide a far more reliable and direct measure of water availability within the soil.

This study 16 used tensiometers installed in 4 railway embankments; 2 on each batter. The depth was chosen to target the soil below the upper 1 m. A typical installed tensiometer is shown in Figure 5. The current negative pressure can be seen on the dial gauge.

Figure 5. An installed soil tensiometer in action.

Readings were taken manually and therefore sporadically. A sample of readings from one embankment are shown in Figure 6.

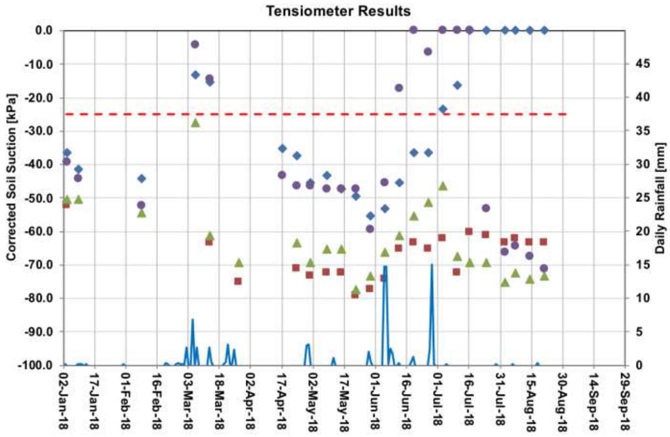

Figure 6. Collated readings from installed tensiometer

Further work is underway to extend validation of the method including instrumentation of natural and constructed slopes including a trial cut.

6 CONCLUSIONS

The method described here is considered sufficiently grounded in theory, flexible in application and with sufficient conservatism to allow the reliable inclusion of soil suction in slope stability calculations. It must be stressed, however, that the conditions encountered for this application were considered well suitable for some reliance on soil suction.

Early results have demonstrated that soil suction is present at all locations and generally above the assumed AEV of 25 kPa. In most bases soil suctions of around 50 kPa to 70 kPa are being measured. Some issues have been encountered with lower than expected results but these have been found to be directly related to installation or operation and not to loss of suction. Rainfall has been found to have some minor impact on measured suctions.

The regulator has accepted this approach as part of the approval process. Further research is underway to undertake the following:

- Monitor soil suction in the longer term (1-2 years)
- Improve data collection in terms of installation and reading frequency
- Understand the effects of rainfall on suction at depth
- Trial alternate soil suction measurement devices

The authors would like to thank the respective mining companies for having the foresight to support the development and implementation and the regulator for their receptiveness of this relatively novel approach. We would also like to thank other members of the technical committee who have assisted with the application and verification of this method. We would also like to thanks Amin Pasha for reviewing this document and providing constructive comments.

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