Unsaturated soil mechanics and implications for clayey soils compacted dry of standard optimum water content

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ABSTRACT

Developments in the mechanics of unsaturated soils are investigated in relation to current engineering standards/practice. The behaviour of unsaturated soils is exceedingly complex and the behaviours experienced are not readily explained using ‘classical’ saturated soil mechanics principles. Jennings and Burland (Jennings and Burland, 1962) established that Terzaghi’s (1936) principle of effective stress was invalid for clayey soils with degrees of saturation less than approximately 90%. Depending on the stress range, samples may either shrink (collapse) or swell (heave). This potential for collapse of compacted soils was recognised by Lawton et al. (Lawton et al., 1992) as being poorly understood area by geotechnical engineers. In semi-arid climates, like much of Australia, the development of unsaturated soil mechanics can play an important role in safe and economical design of infrastructure.

Keywords: unsaturated soils, earthworks, compaction

1 INTRODUCTION

Unsaturated soil mechanics is a continuing research area in geotechnical engineering. In Australia, much of the soils that we work with as geotechnical engineers are unsaturated – both natural (e.g. residual soils) and man-made (e.g. compacted soils).

The role of the geotechnical engineer is shifting from maintaining stability (e.g. of an embankment slope) to maintaining deformations of earth structures to within tolerances. Boundary value problems are typically solved through the use of finite element software and require a suitable constitutive model to capture volume change, shear strength and hydraulic behaviours. Numerous constitutive models for unsaturated soils have been proposed in the literature.

Historically, highly plastic clays could be avoided for use in construction by spoiling and importing better quality material for use in earthworks. Today however, the earthworks component in any major infrastructure project (e.g. a highway/freeway) may comprise a significant proportion of the total construction budget and there will inevitably be pressures on utilising all available material. The process of compaction inevitably results in an unsaturated soil and understanding the behaviour of this type of material is essential for design.

Unsaturated soils have received significant interest in the geotechnical research community. The vast majority of this research is however on compacted soils typically prepared dry of standard proctor optimum. Compacted soils, for research purposes, are either prepared to a low dry density (high void ratio) to capture collapse phenomenon or high dry density (low void ratio) to simulate in situ conditions for high level radioactive waste disposal facilities. Common engineering applications for compacted soils today (e.g. embankments for highways and dams) are typically placed with some control over the placement conditions and would be somewhere in between that which is typically tested in research. Compaction is actually a form of ground improvement (Terzaghi et al., 1996) but today in common engineering application compaction receives little attention with run-of-the-mill/one size fits all standards commonly produced based on precedence or code (Walsh et al., 1997).

2 EFFECTIVE STRESS AND STRESS STATE VARIABLES

The complexities of unsaturated soil largely revolve around the definition of suitable stress state variables (e.g. Terzaghi’s effective stress, Bishop’s effective stress, average skeleton stress and net stress/suction) and volume change. Terzaghi (Terzaghi, 1936) proposed the principle of effective stress:

$$\sigma' = \sigma - u = \sigma - u_w \tag{1}$$

Where σ is the total stress, u_w is the pore-water pressure and σ` is the effective stress. This definition of an effective stress has been found, at stress levels of interest, to provide an accurate description of the mechanical behaviour of saturated soil. Interestingly, Muir Wood (1990) takes the effective stress principle as a “hypothesis or conjecture weakly non-falsified”. Terzaghi’s definition of effective stress has largely been disputed for unsaturated soils through laboratory testing, such as Jennings and Burland (1962). Through laboratory tests on air dried material, the one dimensional compression curves were shown to be different to that of the saturated sample shown in Figure 1(a).

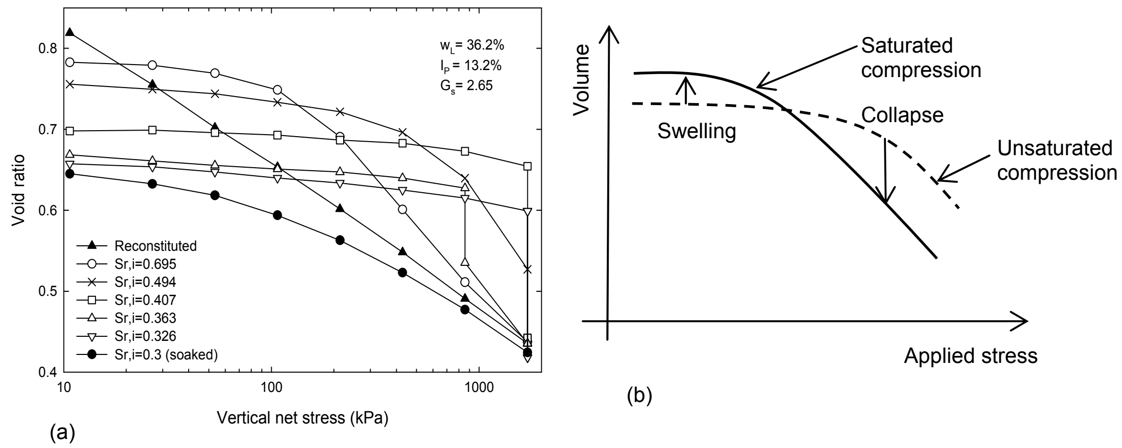


Figure 1: (a) Air dried compression curves of Jennings and Burland (1962). (b) Typical volume change behaviour of unsaturated soils.

Bishop and Blight (1963), state that “Since soils are not ideal elastic materials, the equivalence of changes in pore pressure and changes in total stress” satisfying the principle of effective stress “depends on the same stress paths being followed and on the same rates used, otherwise errors will occur similar to those which results when the principle of superposition is applied to a structure not obeying Hooke’s law”. The derivation of Bishop’s effective stress is based on a simple extension of Terzaghi’s effective stress Eq. (1) to include the pore-air pressure. Skempton (Skempton, 1960) demonstrated that Terzaghi’s definition was not strictly true and introduced a factor k_w which depends on the mode of test, either volume change or shear as shown in Eq. *(2)*. The next most logical step was to introduce a similar expression for the pore-air in Eq. *(3)*.

$$\sigma' = \sigma - k_w u_w \tag{2}$$

$$\sigma' = \sigma - k_w u_w - k_a u_a \tag{3}$$

Bishop and Blight (1963) translate change in effective stress (Terzaghi) for saturated soils, to unsaturated soils as “simultaneous equal changes in total stress, pore-water pressure and pore-air pressure will have no measurable effects on volume or strength”. And complete the following manipulation: If $k_a = 1 - k_w$ $k_a = 1 - k_w$ and $k_w = \chi$ then Bishop’s effective stress is given by:

$$\sigma' = \sigma - u_a + \chi(u_a - u_w) \tag{4}$$

Where $(\sigma - u_a)$ $(\sigma - u_a)$ is the net stress and $(u_a - u_w)$ is the matric suction. Alternatively, Bishop’s effective stress may be rearranged as

$$\sigma' = \sigma - u^* \tag{5}$$

Where $u^* = \chi u_w + (1-\chi)u_a$ $u^*(= [\chi u_w + (1-\chi)u_a])$ is the mean pore pressure. As Terzaghi stated for saturated soils, for Bishop’s effective stress to be a true effective stress, then “all measurable effects of a change in stress, such as volume change… are exclusively due to a change in the effective stress". A suitable relationship for the parameter χ has still yet to be found to satisfy both volume change and shear strength. Commonly the degree of saturation is adopted as an approximation.

Fredlund and Morgernstern (1977) demonstrated that the net stress and matric as defined above are suitable variables to describe the behaviour of unsaturated soils. This was theoreticall verified by Houlsby (1997). The net stress and suction have a significant advantage over Bishop's effective stress in that these variables are controllable in laboratory testing.

3 BARCELONA BASIC MODEL

Hierarchal constitutive models, where an accepted model for saturated soils is modified to capture the behaviour of unsaturated soils are preferred. Here, due to space limitations, the Barcelona Basic Model (BBM) proposed by Alonso et al. (1990) will be briefly reviewed. Numerous other models are available in the literature and a recent review can be found in Sheng (2011).The selection of an appropriate model largely revolves around the personal preference for the choice of constitutive stress variables and conjugate strain variables. The BBM adopts the net stress and matric suction as constitutive variables.

The BBM is the first in a line of constitutive models extended from the well-known Modified Cam Clay (MCC) proposed by Roscoe and Burland (1968). For a saturated (s=0) sample, the volumetric model is shown in Figure 2(a) and the yield surface in net stress (p) and deviator (q) stress space is the elliptical surface of the MCC. A key feature of the model proposed by Alonso et al. (1990) is the introduction of a loading-collapse yield surface in the stress-suction space as shown in Figure 2 (b). The loading collapse yield surface defines the evolution of the yield stress of an unsaturated soil (p_c) with suction.

As discussed above, the volume change behaviour of unsaturated soils are the most complex. The volume change equation of the BBM model is given by Eq. (6). On wetting (suction reduction) at low confining stress, BBM predicts swell, whereas at higher stress, collapse is predicted. Perhaps the greatest criticism of the BBM is that the model predicts an ever increasing collapse potential with high stress.

$$v = 1 + e = N(s) - \lambda(s)\ln\frac{\bar{p}}{\bar{p}_r} \tag{6}$$

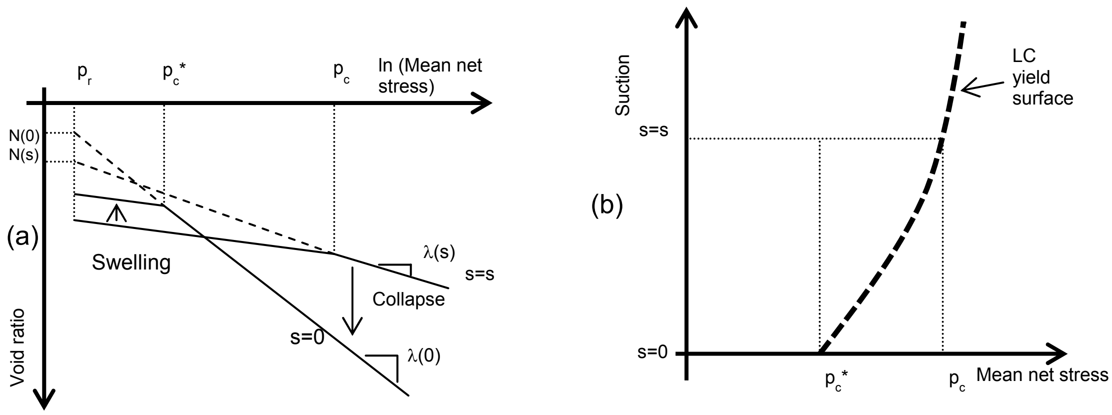


Figure 2: Barcelona Basic Model; (a) Volumetric model (b) Loading-collapse yield surface (Alonso et al., 1990)

4 COMPACTED FILL AND ENGINEERING PRACTICE

Proctor (1933) developed what has now become known as the Standard Proctor compaction test (or water content/density relationship) with a compaction energy of 592.7 kJ/m3. This compactive effort was found to closely resemble the energy exerted by equipment used in the construction of embankment dams at that time. Proctor identified that compaction of a soil is dependent on the water content, soil type and compactive effort. The process of compaction (flow of air) should however not be confused with the process of consolidation (flow of water). With the advent of larger/heavier construction equipment the Modified Proctor compaction test has been introduced with compaction energy of 2693 kJ/m3. During the compaction process, the water content of the soil can be assumed to remain essentially constant as shown in Figure 3.

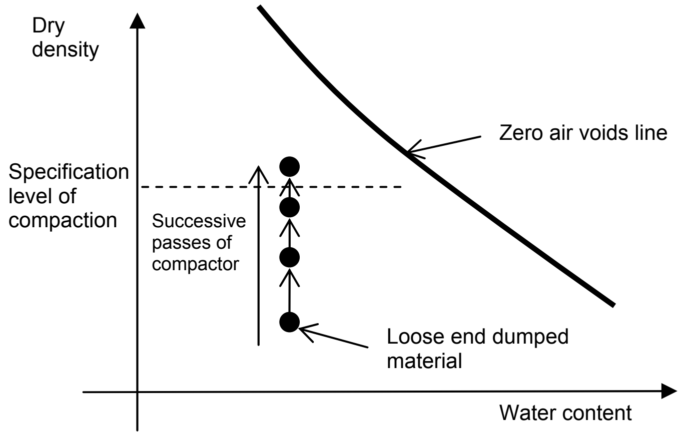


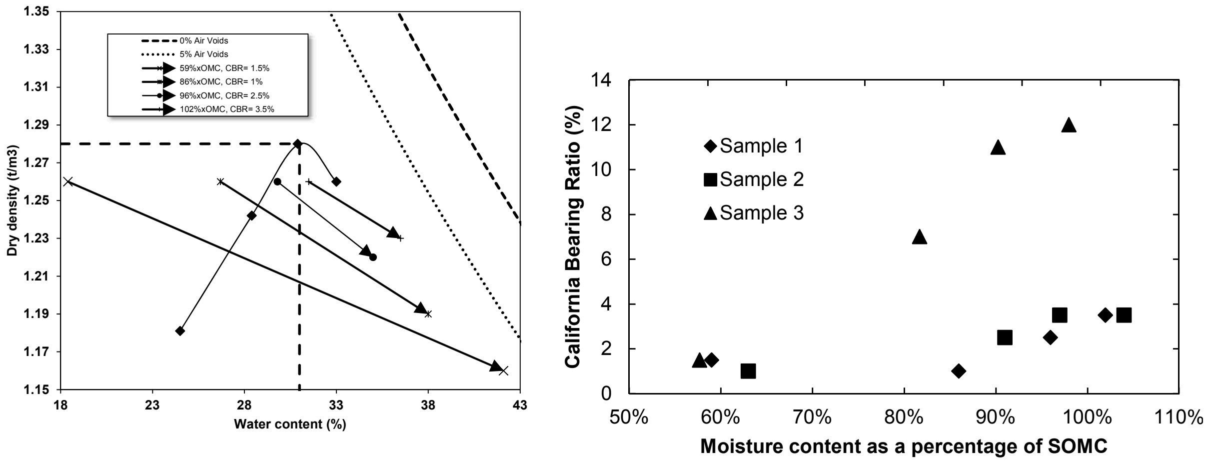
Figure 3: Schematic of compaction process

High plastic clays, when placed at or above the standard optimum moisture content will most likely have a low California Bearing Ratio (CBR). Low CBR material can however be accommodated for in both flexible and rigid pavement designs through suitable layering. Colenbrander and Smith (2007) demonstrated that soils commonly meeting the design assumptions will be failed by inspectors when proof rolled. This appears largely due to an adopted proof rolling specification that does not take into account design assumptions. It appears to the authors, that currently some construction specifications that allow compaction at moisture contents much less than the standard optimum moisture content are being adopted. This is due to the fact that at the time of construction the material will have a higher CBR (e.g. similar to a CBR test without soak) and maybe be passed by proof rolling. Placement of fill in such a way however can cause more headaches in the long-term than the extra effort required during construction.

4.1 Swelling

In a recently completed design investigation phase for a major highway project (see also (Aryal et al., 2012)), several CBR (4-day soaked, 4.5kg surcharge) tests at various remoulded water contents were completed to assess the sensitivity of some poorer quality material proposed for use in the earthworks. The material shown had liquid limits between 36% and 50% and plasticity index between 11% and 18%. The results for density and water content pre and post soaking in the CBR tests for one type of material are shown in Figure 4(a). The target moisture contents for remoulding the CBR samples were 60% of SOMC, 90% of SOMC, SOMC minus 2% water content, SOMC plus 2% water content. The samples were compacted to a target of 98% SMDD. The reported CBR for three types of material are shown in Figure 4(b).

The results of this CBR tests are quite interesting as, samples compacted close to the SOMC have a higher CBR following soaking and samples compacted closer to the SOMC swelled less and had a smaller change in moisture content. These results are similar to the concept reported by Cavagnaro (2004) who noted that a significant proportion of poor ride quality on roads in South Australia may be due to poor material selection and placement. With the tests above, it is shown that for some commonly adopted construction specifications, where material is allowed to be placed significantly below the SOMC, the support provided to the pavement by the subgrade (i.e. CBR) is reduced following soaking.



(a) (b)

Figure 4: (a) Results of 4-day soaked CBR tests at various remoulding water contents in compaction plane for Sample 1 (b) Increase of CBR (after soak) with compaction moisture content.

A thorough review of post construction testing on a number of construction projects that resulted in legal proceedings was completed by Burman et al. (2008). They note that there is “often significant differences of opinion by experts for the parties involved”. This is largely related to the complexities of unsaturated soils – e.g. swell/collapse and dependence of shear strength on suction. In the cases reported by Burman et al. legal proceedings resulted because of a perception of poor construction due to an apparent loss of relative compaction sometime after completion.

The conclusions of Burman et al. and the simple laboratory test results above (Figure 4) demonstrate, in a simplistic way, the effects that moisture has on the engineering behaviour of compacted clays. In all cases after soaking the relative compaction reduced due to swelling. This effect is more pronounced for material placed well dry of optimum.

4.2 Collapse potential

The reduction in volume of unsaturated soils when wetted has typically been called collapse. The word “collapse” itself may be too strong a word – the notion of collapse brings to mind catastrophic events (e.g. a building or bridge collapse). However, Alsonso et al. (Alonso et al., 2010) reported a case study of a collapsed road embankment built during 1994 in Girona, Spain. The collapse was induced following high rainfall and caused “extensive” damage to the new road. The embankment comprised low to medium plasticity sandy clay (decomposed granite) with liquid limits between 31-46% and plasticity indexes between 7-24%. Collapse settlements approached 300mm with the most serious damage occurring around the bridge abutments. Oedometer tests, following stress paths likely to have been experienced by the embankment, were performed on samples recovered from the embankment. Results indicated collapse in the order or 0.5% to 4% on inundation/wetting. The results of the construction compaction test results are shown in Figure 5 along with the standard Proctor maximum dry density and optimum moisture content.

Converting the raw compaction results to relative compaction and moisture content as a percentage of OMC (w/SOMC) demonstrates that the material was placed well dry of optimum (49% to 94% of SOMC) and achieved a minimum compaction of 95% SMDD. In fact, the construction average was for greater than 100% SMDD. Based on this, it appears that the placement moisture content has a more pronounced effect than the relative compaction on the collapsibility.

5 CONCLUSIONS

The behaviour of unsaturated soils is exceedingly complex, as evidenced by over 5 decades of research on the subject. The role of the geotechnical engineer, shifting from maintaining stability to limiting deformations within tight tolerances, requires an understanding of the behaviour of unsaturated soils, not just the “classical” principles of saturated soils. The behaviours of unsaturated soils can be accommodated through rational implementation of construction specifications rather than a one size fits all approach. The implications of poor construction specifications may take years to become evident, and by that time, pin pointing the cause of distress is likely to be extremely difficult.

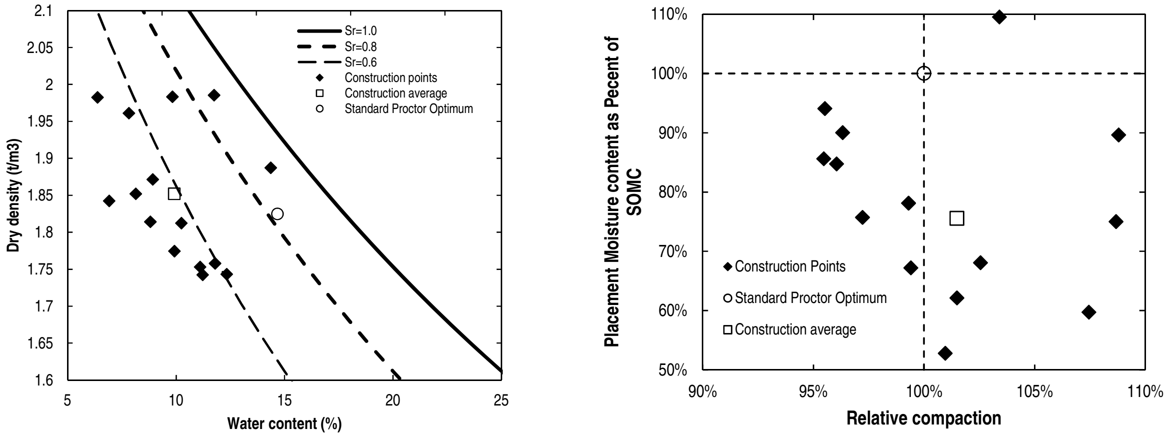


Figure 5: Construction test results from collapsed road embankment Girona, Spain (Alonso et al., 2010)

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