Procedia Engineering
Volume 143, 2016, Pages 308–314
Advances in Transportation Geotechnics 3 . The 3rd International Conference on Transportation Geotechnics (ICTG 2016)

Soil Water Retention Behaviour of a Sandy Clay Fill Material

D.G. Toll[1*], J.D. Asquith[1], P.N. Hughes[1] and P. Osinski[2]
[1]School of Engineering and Computing Sciences, Durham University, UK
[2] Department of Geotechnical Engineering, Warsaw University of Life Sciences, Warsaw, Poland

Abstract
The performance of transportation networks is critically dependent on the performance of cutting and embankment slopes. An instrumented embankment has been established at Nafferton farm in North East England to investigate the response of an embankment to changing climatic conditions. Higher pore water pressures (near to hydrostatic) were observed during winter months (typically January) falling back to lower values in March. The pore water pressures showed generally positive values in the upper 3 m of the embankment although suctions existed at 4.5 m depth. Soil water retention curves (SWRC) are essential to understand the changes in water content and suction that can take place during seasonal cycles and during extreme weather events. SWRCs for the embankment soil have been measured in the laboratory using novel high suction tensiometer based equipment. The results confirm that wetting and drying paths for the soil show significant hysteresis. The major differences occur in the first cycle of drying and wetting and smaller differences are seen in subsequent scanning curve paths.

Keywords: Embankment; Unsaturated soil; Soil water retention curve; Tensiometer

1 Introduction

The UK's transport infrastructure is one of the most heavily used in the world. The performance of the transportation networks is critically dependent on the performance of cutting and embankment slopes. Many of these slopes are old and suffer high incidents of instability (increasing with time). There is evidence that the scenario of increased (and more intense) rainfall has already had an impact on UK transport infrastructure (Kilsby *et al.*, 2009) and climate change scenarios for the UK present the potential for these issues to accelerate. To investigate these issues, the research project iSMART

* Email: d.g.toll@durham.ac.uk

Selection and peer-review under responsibility of the Scientific Programme Committee of ICTG 2016

doi:10.1016/j.proeng.2016.06.039

(Infrastructure Slopes: Sustainable Management And Resilience Assessment) has been established as a collaboration between six UK academic partners (Universities of Durham, Loughborough, Newcastle-upon-Tyne, Queens Belfast and Southampton and the British Geological Survey) and 11 asset owners and industrial partners. Together, the partners are using a combination of field measurements, laboratory testing and development of conceptual and numerical models to improve our understanding of the interaction between weather, vegetation and soil.

One of the sites being monitored within the iSmart project is an instrumented embankment to investigate the response to changing climatic conditions. The BIONICS embankment was built at Nafferton farm in North East England (Hughes *et al.*, 2009). The fill material was a glacial till (Durham Lower Boulder Clay), a common fill material in North East England and hence representative of earthwork construction. The fill material can be classified as a sandy clay of intermediate plasticity.

An important aspect of embankment fill behaviour is to be able to understand the changes in suction during drying and wetting. The relationship between suction and water content is called the soil water retention curve (sometimes also known as a soil water characteristic curve). A typical water retention curve (in terms of volumetric water content) is shown in Figure 1. It is highly hysteretic in nature. If the soil starts from a saturated state and is subject to drying, it will follow the *Primary Drying Curve*. On wetting from an oven dried state, the soil will follow the *Primary Wetting Curve* (Figure 1). When the suction is reduced to zero, the final volumetric water content may be lower than the initial saturated value, θ_s, either due to air bubbles remaining trapped within the soil, or as a result of irrecoverable shrinkage of the soil.

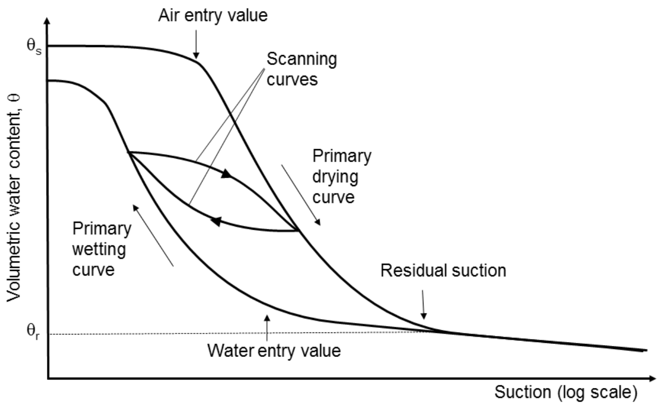

Figure 1. Typical Soil Water Retention Curve (after Toll, 2012)

The primary drying and wetting curves define an envelope of possible states within which the soil can exist. If drying is halted partway down the primary drying curve and wetting is started, the soil will follow an intermediate *Scanning Curve*, that is flatter than the primary wetting curve, until the primary wetting curve is reached. Similarly, if wetting is halted partway up the primary wetting curve and drying is started, the soil will follow another Scanning Curve, that is flatter than the primary drying curve, until the primary drying curve is reached.

The soil water retention curves (SWRC) for the BIONICS soil have been measured in the laboratory using novel high suction tensiometer based equipment.

2 Field Measurements of Suction

The objective of the iSMART project is to investigate what could happen to infrastructure embankments in the UK when subjected to climate change. An experimental embankment has been built in four panels (Figure 2) separated by vertical impermeable membranes and constructed using different compaction efforts (Hughes *et al.*, 2009). Panels A and D are poorly compacted (intended to represent old rail embankments constructed more than 100 years ago) while panels B and C are well compacted (representing modern embankments). Current measurements of suction have been obtained during natural rainfall conditions. A climate control system can be used to impose expected future climate patterns on the embankment, using a system of sprinklers (Hughes *et al.*, 2009).

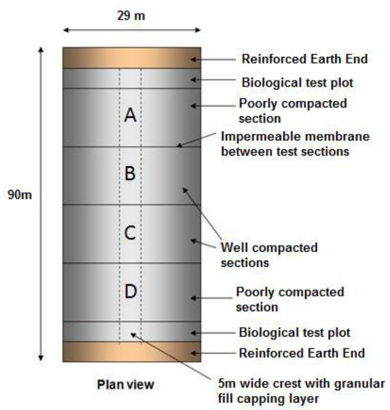

Figure 2. Plan view of BIONICS embankment (after Hughes et *al.*, 2009).

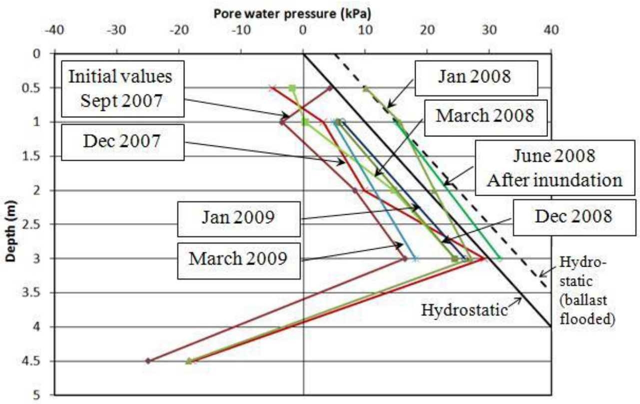

Figure 3. Pore water pressure profiles for well compacted panel B (after Toll et *al.*, 2012).

Part of the instrumentation system installed in the BIONICS embankment used high capacity tensiometers to obtain continuous direct measurements of suction or pore water pressure (Mendes *et al.*, 2008). Ten high capacity tensiometers capable of direct measurement of pore water pressure to -2MPa (Lourenco *et al.*, 2006; Toll *et al.*, 2013) were installed in two borehole probe locators installed below the crest of the embankment. Each locator includes five suction stations at depths of 0.5m, 1m, 1.5m, 2m and 3m. The borehole probe locator consisted of a 3m long PVC pipe with an outer diameter of 90mm. Five guide tubes were inserted inside the borehole probe locator to individually connect each suction station to the surface and allow insertion of the tensiometers. This design allows the tensiometers to be removed individually whenever necessary. This is important as tensiometers can cavitate when measuring high suctions for a long period of time and then require removal for resaturation.

Toll *et al.* (2012) reported the results of monitoring since September 2007 and showed the cycles of pore water pressure that might be expected within the central zone of an embankment (away from the side slopes). Higher pore water pressures (near to hydrostatic) were observed during winter months (typically January) falling back to lower values in March (Figure 3). Lower values might normally be expected during summer months, but the climate during the summers of 2007 and 2008 were "untypical" with high levels of summer rainfall, as well as being subject to artificial inundation using the sprinkler system on the embankment.

The pore water pressures showed generally positive values in the upper 3 m of the embankment although suctions existed at 4.5 m depth. These lower values could represent construction induced suctions, but are also likely to be affected by under-drainage of the embankment by field drains. The values are generally lower than hydrostatic conditions, even in the upper 3 m, except following a period of heavy precipitation during winter 2007/8.

It should be noted that much higher suctions have been observed on the side slopes of the embankment. Glendinning et al. (2014) showed suction of 500-600 kPa being developed within the top 1m of the side slopes.

3 Soil Water Retention Curves

The fill material used in the construction of the BIONICS embankment was tested. It was prepared by sieving through a 2.8mm sieve to remove the larger particles to reduce the variation in properties. The sieved material comprised 30% sand, 35% silt and 35% clay, i.e., a sandy clay soil. The Liquid Limit was 43.3% and the Plastic Limit was 23.7%, resulting in a Plasticity Index of 19.6 (Mendes, 2011). The particle density was 2.66 Mg/m^3. Specimens for testing were prepared by compaction into a 100mm diameter mould using the equivalent compactive effort of the standard Proctor test (BS light compaction) (BS1377, 1990). Samples were compacted wet of optimum at a water content of 24%. This resulted in specimens close to saturation (degree of saturation, Sr > 95%). From the larger compacted samples, smaller specimens having a diameter of 75mm and a thickness of 20mm were trimmed from the 100mm diameter compacted samples for testing in the tensiometer equipment.

4 The Durham SWRC Equipment

Measurements of the soil water retention curves (SWRC) were carried out using the Durham SWRC equipment (Toll *et al.*, 2015). The experimental apparatus allows continuous measurements of water content, suction and volume change. The apparatus is made up of a PVC frame (Figures 4 & 5) placed on an electronic balance to determine the change in sample weight and hence water content (as used by Lourenço *et al.*, 2007; 2011).

Figure 4. The Durham SWRC equipment, showing the frame sitting on the electronic balance.

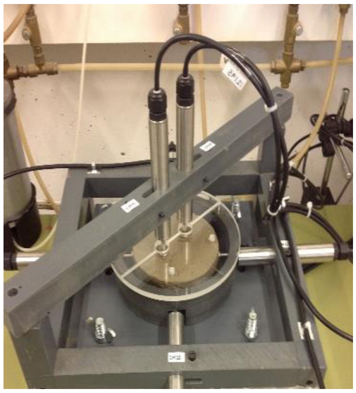

Figure 5. The Durham SWRC equipment, showing the PVC frame with LVDTs to measure volume change.

For volume change measurements, four displacement transducers were installed through the four outside beams of the frame to measure radial displacement of the specimen and two more dis placement transducers were fitted through the upper beam to measure axial displacement (change in height) (Figure 5). Volume change of the specimen could then be calculated from the radial and axial deformations. A Durham University high suction tensiometer (Lourenco *et al.*, 2006; Toll *et al.*, 2013) was used to measure suction. The tensiometer was fitted through a hole in the support plate, with a tight fitting rubber O-ring to secure it in place. All transducers were connected to a real-time data acquisition system (Toll, 1999). Using the tensiometer technique, suction can be measured in samples either dried continuously while exposed to the atmosphere (continuous procedure) or by drying in stages (stage procedure). In the stage procedure, the specimen is sealed and allowed to equalise internally after each period of drying. Both approaches are quicker than traditional methods for obtaining SWRCs (e.g. pressure plate).

The results of a series of laboratory measured soil water retention curves obtained using the tensiometer technique are plotted in Figure 6. The results were obtained by continuous drying are show as continuous traces. The results of stage drying tests are shown as individual data points (triangles). Good agreement is shown between all sets of results over the range 1 - 1000 kPa.

One set of tests followed the SWRC over two complete cycles of drying and wetting. Figure 7 shows that for each full cycle (drying and wetting) the hysteretic behaviour is quite different. For the first cycle, the difference between the primary drying curve and the subsequent wetting curve is much larger than for the second cycle. The last three paths (wetting - drying - wetting) lie very close to each other.

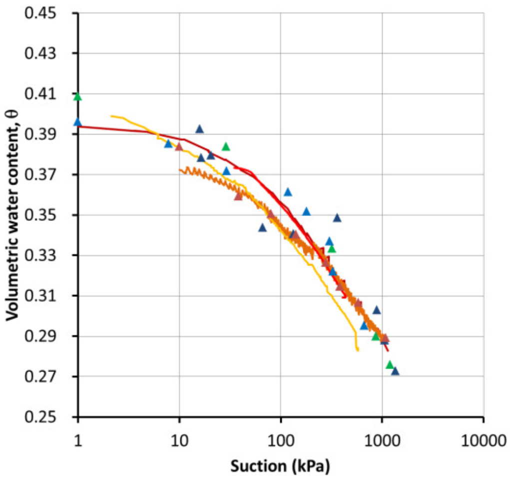

Figure 6. SWRCs for drying measured by the tensiometer approach.

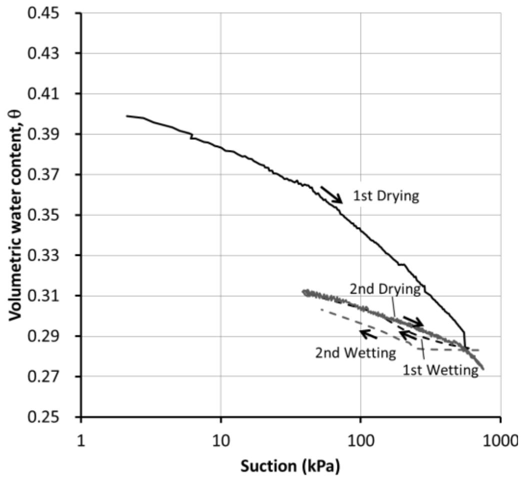

Figure 7. SWRCs for repeated drying and wetting cycles (continuous approach).

Conclusions

A large part of any transportation network comprises slopes (in embankments and cuttings) and so it is important that we understand the impact of climate change on this part of our infrastructure. This paper reports on studies involving field measurements of pore water pressure responses to current climatic conditions. It also discusses the soil water retention behaviour of embankment fill material, which is essential for modelling the complexity of climate/soil interaction.

Results of field monitoring within the central zone of the BIONICS embankment in the UK shows higher pore water pressures (near to hydrostatic) during winter months (typically January) falling back to lower values in March. The pore water pressures showed generally positive values in the upper 3 m of the embankment although suctions existed at 4.5 m depth. Much higher suctions (500 to 600 kPa) have been observed on the sides slopes of the embankment.

New laboratory equipment is described for measurement of soil water retention curves, using a high capacity tensiometer. It provides continuous measurements of water content (from an electronic balance), suction (from a high suction tensiometer) and volume change (using LVDTs to measure changes in diameter and height). The equipment has been used to determine the soil water retention behaviour in terms of volumetric water content.

The results confirm what is well known, that wetting and drying paths for soil show significant hysteresis. The major differences occur in the first cycle of drying and wetting and smaller differences are seen in subsequent scanning curve paths.

Acknowledgements

The authors wish to acknowledge funding from the Engineering and Physical Sciences Research Council for the BIONICS project (GR/S87430/01) and the iSMART project (EP/K027050/1) and EU COST Action TU1202 "Impact of climate change on engineered slopes for infrastructure".

References

BS1377 (1990) *Methods of test for soils for civil engineering purposes,* British Standards Institute, Milton Keynes.

Glendinning S, Hughes P, Helm PR, Chambers J, Mendes J, Gunn D, Wilkinson P, Uhlemann S. (2014) *Construction, management and maintenance of embankments used for road and rail infrastructure: implications of weather induced pore water pressures.* Acta Geotechnica, 9 (5), 799-816.

Hughes, P.N., Glendinning, S., Mendes, J., Parkin, G., Toll, D.G., Gallipoli, D. and Miller, P. (2009) *Full-scale testing to assess climate effects on embankments.* Proc. Institution of Civil Engineers, Engineering Sustainability, 162, 2, pp. 67 - 79.

Kilsby, C.G., Glendinning, S., Hughes, P.N., Parkin, G. and Bransby, M.F. (2009) *Climate-change impacts on long-term performance of slopes.* Proceedings of the Institution of Civil Engineers, Engineering Sustainability, 162, 2, 59–66.

Lourenço, S.D.N., Gallipoli, D., Toll, D.G. and Evans, F.D. (2006) *Development of a Commercial E 3S Web of Conferences Tensiometer for Triaxial Testing of Unsaturated Soils,* Proc. 4th International Conference on Unsaturated Soils, Phoenix, USA, Geotechnical Special Publication No. 147, Reston: ASCE, Vol.2, pp. 1875 - 1886.

Lourenço, S.D.N., Gallipoli, D., Toll, D.G., Evans, F.D. & Medero, G.M. (2007) *Determination of the Soil Water Retention Curve with Tensiometers,* in Experimental Unsaturated Soil Mechanics, (ed. T. Schanz), Springer, pp. 95 - 102.

Lourenço, S.D.N., Gallipoli, D., Toll, D.G., Augarde, C.E. & Evans, F. (2011) *A new procedure for the determination of the Soil Water Retention Curves by continuous drying using high suction tensiometers.* Canadian Geotechnical Journal , 48, 2, pp . 327 - 335.

Mendes, J. (2011) *Assessment of the impact of climate change on an instrumented embankment: an unsaturated soil mechanics approach.* PhD Thesis, Durham University. Available online: http://etheses.dur.ac.uk/612/ .

Mendes, J., Toll, D.G., Augarde, C.E. & Gallipoli, D. (2008) *A System for Field Measurement of Suctions using High Capacity Tensiometers,* Unsaturated Soils: Advances in Geo-Engineering, Proc. 1st European Conf. Unsaturated Soils, pp. 219-225.

Toll, D.G. (1999) *A data acquisition and control system for geotechnical testing,* in Computing Developments in Civil and Structural Engineering (eds. B. Kumar and B.H.V. Topping), Edinburgh: Civil - Comp Press, pp 237 - 242.

Toll, D.G. 2012. *The behaviour of unsaturated soils.* Chapter 5 in Handbook of Tropical Residual Soil Engineering, (eds. Huat, B.B.K., Toll, D.G. & Prasad, A.) London: Taylor and Francis.

Toll, D.G., Mendes, J., Gallipoli, D., Glendinning, S. and Hughes, P.N. (2012) *Investigating the Impacts of Climate Change on Slopes: Field Measurements,* in Earthworks in Europe, Geological Society of London, Special Publication Vol. 26, pp.151-161.

Toll, D.G., Lourenço, S.D.N. and Mendes, J. (2013) *Advances in suction measurements using high suction tensiometers,* Engineering Geology , 165, pp 29 – 37.

Toll, D.G., Asquith, J.D., Fraser, A., Hassan, A.A., Liu, G., Lourenço, S.D.N., Mendes, J., Noguchi, T., Osinski, P., Stirling, R.A. (2015) *Tensiometer techniques for determining soil water retention curves.* Proc. 6th Asia-Pacific Conference on Unsaturated Soil. Guilin, China. London: Taylor & Francis (2015).