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Retaining wall design in expansive clay for the Darlington Upgrade Project

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ABSTRACT: The Darlington Upgrade Project (DUP) is an important part of the development of Adelaide's North-South Corridor and will deliver an upgrade to 3.3 km of the existing Main South Road between the Southern Expressway and Tonsley Boulevard. One of the main features of the DUP is a lowered motorway with maximum retained height of 11 m. The design solution comprises a combination of 60° revetment slopes and cantilever, spaced Continuous Flight Auger (CFA) bored pile walls. This paper presents a detailed account of the design of the bored pile walls in unsaturated expansive soils and includes an assessment of soil suction and the selection of design soil suction and shear strength profiles for ultimate and serviceability limit state conditions. The assessment of potential swelling pressures, and the design measures adopted to minimise loss of soil suction and associated strength and stiffness are also presented.

1 INTRODUCTION

1.1 *Background*

The Australian and South Australian Governments are working collaboratively to create a non-stop North-South Corridor, a major traffic route in Adelaide that will run between Gawler and Old Noarlunga, covering a total distance of 78 km. The Darlington Upgrade Project (DUP) is an important part of the development of Adelaide's North-South Corridor and will deliver an upgrade to 3.3 km of the existing Main South Road between the Southern Expressway and Tonsley Boulevard.

One of the main features of the DUP is a lowered non-stop motorway. The lowered motorway is retained by a combination of CFA bored pile walls and 60° revetment slopes. The design of revetment slopes is described by Pointon *et al.* (2018). The bored pile walls are generally required immediately after bridge abutments and at areas where space is inadequate for the construction of revetments. The total length of bored pile walls is approximately 2 km with maximum retained height of 11 m.

The South Australian Department of Planning, Transport and Infrastructure's (DPTI) design specification for the DUP retaining walls requires that post-construction horizontal movement at the top of walls should be the lesser of 0.5% of wall height, or 50 mm (DPTI, 2015). The bored pile walls comprise cantilever, spaced CFA piles, typically 900 mm diameter at 1500 mm centres.

This paper presents the design methodology of the bored pile walls in unsaturated expansive clay.

1.2 *DPTI design standard*

Standards and guidelines for retaining wall design such as AS 4678, AS 5100, Eurocode 7 and CIRIA C760 do not provide specific guidance on the design of retaining walls in unsaturated expansive soils.

In 2014, DPTI constructed a trial pile wall in order to assess wall behaviour in stiff unsaturated soils. The intention of the study was to investigate the feasibility of implementing a more economical retaining wall system for infrastructure projects in South Australia. Piles with three different diameters, 450 mm, 600 mm and 800 mm, with pile spacings from 800 mm centres to 1350 mm centres, were constructed without a capping beam to support an excavation of 8 m maximum depth. As part of the study, retained ground behind the cantilever bored pile walls was subjected to wetting for over three months to simulate saturated ground conditions in the top few metres. The maxi-mum total individual pile horizontal movement at the top of the wall was less than 0.7% of the retained height. If a capping beam had been constructed, it is likely that maximum pile movements for individual piles would have been reduced due to load re-distribution.

Inspired by its findings, DPTI published a design standard for retaining walls in 2015. The standard describes key design requirements in unsaturated soils, in addition to typical considerations for retaining wall design in saturated soils.

Soil above permanent groundwater level is unsaturated and undergoes both seasonal and long-term suction changes. The DPTI design standard requires consideration of suction changes from the time of construction to the long-term equilibrium condition and the resulting volumetric changes. Soil expansion due to loss of suction and increases in moisture content can result in swelling pressures on the wall and additional wall movement. The extent of wall movement due to soil swelling must be calculated and considered in the design. Leaking water pipes or perched groundwater can cause reductions in soil suction and shear strength. However, such an event would be considered unusual and would likely only affect a short section of retaining wall.

DPTI's design standard requires that the shear strength of an unsaturated clay, τ, is estimated using either Equation 1 by Fredlund & Rahardjo (1993), or Equation 2 by Briaud (2013):

$$\tau = c' + \sigma' \tan \phi' - u_w \tan \phi^b \tag{1}$$

$$\tau = c' + \left[\sigma' - \chi u_w\right] \tan \phi' \tag{2}$$

where c' = effective cohesion; σ' = effective stress; Φ' = effective friction angle; tan Φ^b = rate of increase in shear strength with the increase in soil suction; and u_w is simplified to total suction. χ is an effective stress parameter where a value of 1 represents fully saturated soil and a value of 0 represents dry soil. Khalili & Khabbaz (1998) showed that by plotting the values of χ against suction ratio, a best-fit relationship was obtained as follows:

$$\chi = \left[\frac{u_w}{u_{wae}}\right]^{-0.55} \tag{3}$$

where u_{wae} is the suction value, or air entry value (AEV), where air starts to penetrate into soil.

2 GEOTECHNICAL PROPERTIES

2.1 *Ground conditions*

The DUP is located within the Adelaide upper outwash / alluvial plain where the soils are typically composed of Tertiary / Quaternary sediments. The near surface deposit is red-brown clay with occa-sional sand and gravel zones belonging to the Pooraka Formation, which has a total thickness of around 3 m to 4 m. The Pooraka Formation overlies older sediments known as Hindmarsh Clay, which typically comprise pale green-grey to reddish-brown clay with occasional sand and gravel lenses. The boundary between the clay units is generally indistinguishable and gradational, and the change of soil properties is subtle. Fissures and near vertical cracks caused by desiccation and shrinkage were found at several locations but are not believed to be widespread in the DUP area.

Underlying the Hindmarsh Clay is a siltstone layer that is typically more than 20 m deep below existing ground level. The founding levels of all the DUP retaining walls lie within the Hindmarsh Clay formation.

Groundwater levels, which are typically 10 m to 20 m below ground level, lie below the formation level of the lowered motorway. Perched groundwater occurs locally within gravel and sand pockets and calcareous zones within the clay units.

The relatively deep groundwater level and predominantly hard clay ground conditions are ideal for wall design using unsaturated soil mechanics.

2.2 *Soil properties*

Particle size gradings of DUP soils indicate that it is predominantly clay. The minimum fines content in coarser grained layers is at least 20%.

Clay plastic limits typically fall between 10% and 25% while liquid limits typically range from about 20% to 90%. The natural moisture content of the clays generally lies close to the plastic limit. Using Austroads (2017) approach to soil reactivity classification, the soils' expansive nature varies from low to very high and is predominantly moderate (Figure 1).

Effective strength parameters drained cohesion, c' and internal friction angle, Φ' were determined from the results of consolidated isotropically undrained (CIU) triaxial tests on saturated soil samples. The design parameters adopted for the Pooraka Formation were c' = 5 kPa and Φ' = 28°, and for Hindmarsh Clay were, c' = 10 kPa and Φ' = 25°.

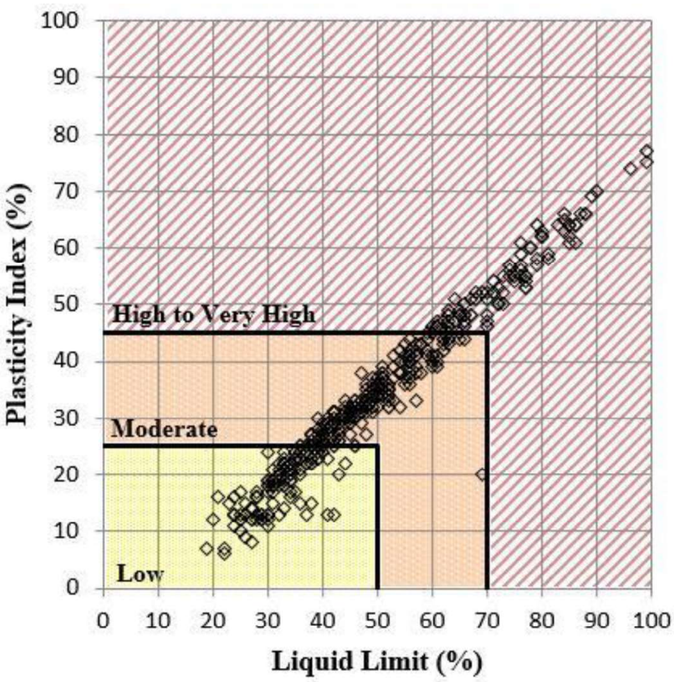

Figure 1. Soil reactivity classification (Austroads, 2017)

Undrained shear strengths from Standard Penetration Test (SPT), Cone Penetrometer Test (CPT), pocket penetrometer and unconsolidated undrained (UU) test, typically ranged from 100 kPa to 1000 kPa.

A site wide relationship between undrained shear strength, S_u and SPT 'N' value of $S_u = 9.6 \times$ SPT 'N' was derived. Lower quartile (Q1) undrained shear strength values were adopted for design in saturated soils.

Assessment of undrained Young's modulus (E_u) was made based on correlations with undrained shear strength and seismic shear wave velocity from vertical seismic profiling tests. The selected shear strain for design was 0.06%, which is within the typical range for retaining wall soil deformation (Mair, 1993). A correlation between E_u and S_u (Q1) of $E_u = 350 \times S_u$ (Q1) kPa was adopted. A drained Young's modulus of $E' = 0.75 \times E_u$ (Kay & Avalle, 1982), was adopted. Lateral soil stiffness in unloading due to soil excavation, was taken as three times the loading stiffness.

A coefficient of at-rest earth pressure (K_o) of 1 was adopted for the over-consolidated soils (CIRIA C580, 2003).

2.3 *Unsaturated soil properties*

Soil suction is a key contributor to the soil strength in unsaturated soils. Design soil suction profiles were adopted for serviceability limit state (SLS) and ultimate limit state (ULS) conditions.

For the SLS case, trapped moisture behind retaining walls is assumed to reduce soil suction in the long-term to an equilibrium suction value of about 3.8 pF, which represents a cautious estimate compared with reported equilibrium suction values for Adelaide of between 3.95 pF and 4.15 pF (various authors). For the ULS case, perched groundwater or water from a leaking water main is assumed to reduce the soil suction further to about 3.4 pF. The magnitude of pF change from SLS to ULS is based on measurements of soil suction as a result of a perched water presented in Mitchell (2016). Figure 2 shows typical design suction profiles. Soils within 2 m above the design groundwater level were assumed to be fully saturated as a buffer for fluctuation in groundwater level and capillary action.

Laboratory soil water characteristic curve (SWCC) tests were carried out on four soil samples to determine the relationships between the degree of saturation and soil suction and were used to establish an AEV of 200 kPa for design purposes (Figure 3).

Apparent cohesion, or suction induced strength, can be estimated using either Equation 1 or 2. For Equation 1, an appropriate value for Φ_b was not readily apparent based on the available data. However, based on previous studies, a value of $\Phi_b = 10^o$ for Keswick Clay was reported by Woodburn & Herraman (2014).

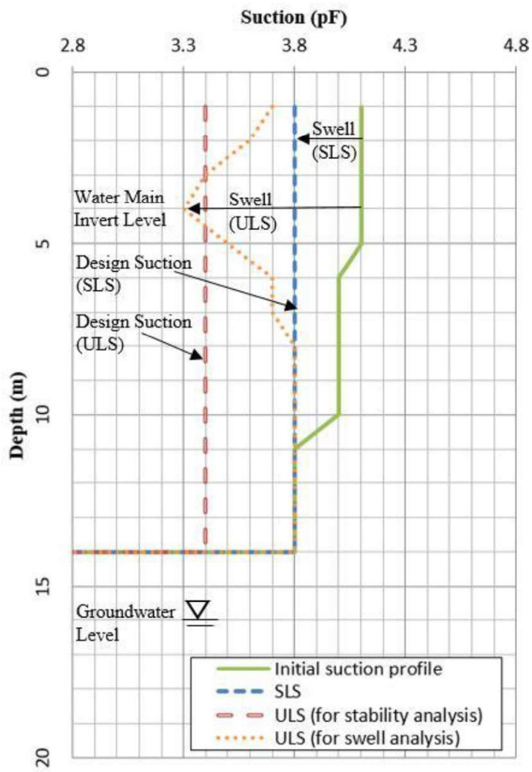

Figure 2. Design suction profiles

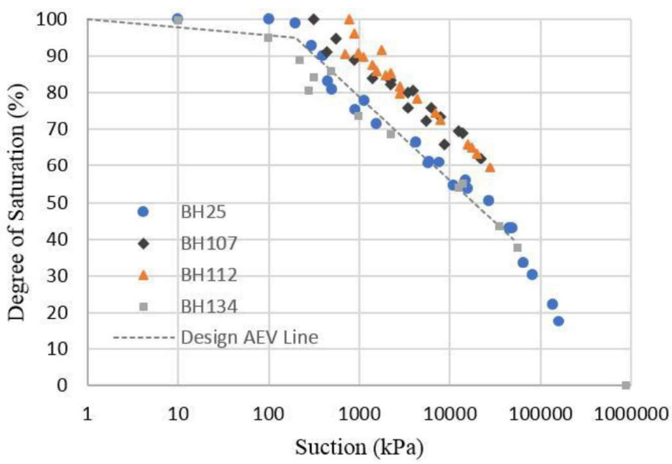

Figure 3. Design soil water characteristic curve to establish AEV of 200 kPa

Goh *et al.* (2010) proposed a non-linear approach where Φ_b is equal to Φ' for suctions lower than the AEV. Hence, for Hindmarsh Clay, Φ_b can be taken as 25^o where suction is less than an AEV of 200 kPa. Figure 4 shows the apparent cohesion for different values of Φ_b and Φ' using Equations 1 and 2. From observations of Figure 4, Equation 1 using $\Phi_b = 10^o$, appears to underestimate the shear strength. Using the Briaud's approach (Equation 2) with an AEV of 200 kPa provides a more reasonable approximation of apparent cohesion at suction values less than 4.0 pF (1000 kPa). Based on these observations, the determination of apparent cohesion for the design of bored pile walls in unsaturated soils was based on Equation 2.

The results of oedometer Constant Volume Swell (CVS) and Consolidation-Swell (CS) tests were carried out to determine the swell pressure versus strain characteristics of the clays. The results of the tests are shown in Figure 5, which also includes the results of the swell component of Shrink-Swell Index tests. An exponential relationship was used to define the swelling pressure versus strain behavior to calculate volumetric expansion and swelling pressure resulting from a change in suction.

3 RETAINING WALL DESIGN

Geotechnical analysis of CFA bored pile retaining walls was undertaken in accordance with AS 5100.2, AS 5100.3 and DPTI Design Standard: Retaining Walls. In the SLS case, the SLS suction profile and strengths were adopted and the maximum allowable post-construction horizontal wall movement was limited to the lesser of 0.5% of wall height, or 50 mm. In the ULS case, the ULS suction profile, for perched groundwater or a leaking water main, was adopted along with an allowance for over-excavation, high-way loading and vehicle crash impact loads, to deter-mine structural actions and to check for stability.

3.1 *Design methodology*

The design methodology and assumptions adopted in the geotechnical design of the CFA bored pile retaining walls are summarised as follows:

- the lateral earth pressures acting on the retaining walls was analysed using WALLAP;

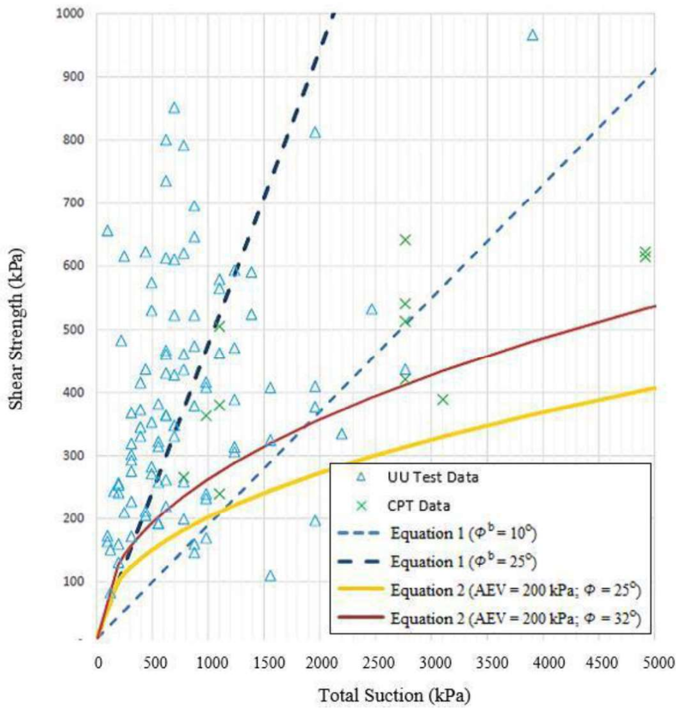

Figure 4. Shear strength versus total suction

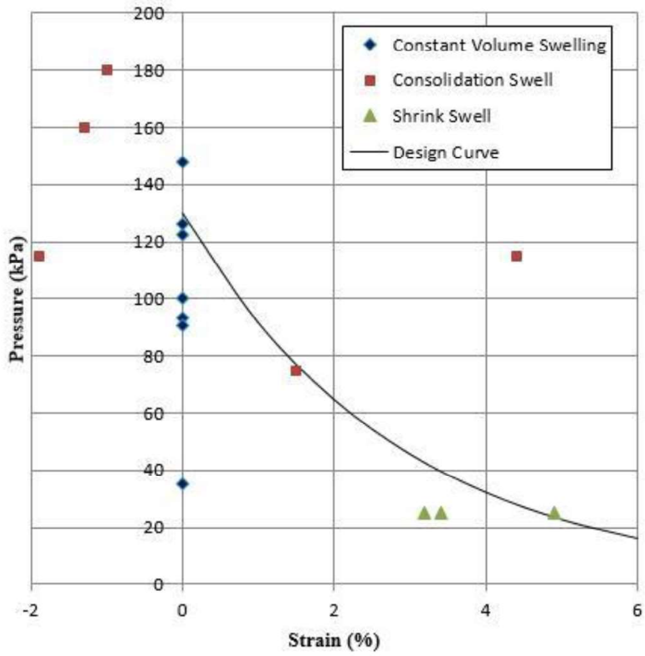

Figure 5. Swell pressure versus strain

- Finite Element Modelling using PLAXIS was carried out to allow comparison of estimated wall de-flections using WALLAP;
- the thickness of the lowered motorway pavement was taken as 1.3 m and is considered as additional depth during construction;
- long-term pile stiffness is reduced by 50% to take account of long term creep (CIRIA C760);
- for long-term analysis, a reduction in soil suction and the corresponding strength and stiffness, was accounted for in the active and passive zones;
- an over dig allowance of 10% of the wall height, was allowed for in ULS design;
- quasistatic earthquake loading was used to model seismic loading effects; and
- as the pile spacing is less than three times the pile diameter, the active and passive earth pressures are assumed to act over the full pile spacing.

Swelling analyses were carried out using two different approaches, firstly, an iterative approach using LPILE, and secondly, a Volumetric Expansion Method (VEM) using PLAXIS 2D.

3.2 *Swelling analyses - iterative approach*

The analysis of expansive soil subjected to swelling is not possible using WALLAP. The first method adopted was to use an iterative approach using spreadsheet calculations and LPILE.

The iterative approach was based on a method presented in the Torrens Road to River Torrens (T2T) Trial Pile Wall Study (DPTI, 2014). The methodology requires knowledge of wall rigidity, swell pressure versus strain relationship and the suction change profile versus depth.

An initial arbitrary pressure profile was used to compute the deflection of the wall using wall stiffness and subgrade soil reactions in front of the wall. The computed deflections were then used to determine the equivalent strain in the soil over an assumed lateral extent of wetting. The swelling pressures were then calculated using the equivalent strain and compared with the initial pressures used to compute wall deflection. This process was then iterated until convergence was reached with an acceptable margin of error. The following assumptions were made:

- as the swelling pressure versus strain relationship was obtained from one dimensional oedometer tests, the strains for a given pressure were divided by two to allow for three-dimensional swelling; and
- strain was reduced by the ratio of the in situ suction change to an assumed change in soil suction for the oedometer tests.

Although this method tended to over predict the deflections and bending moments of the T2T trial pile wall by approximately between 0% and 30%, and 40% and 60%, respectively, it was considered to pro-vide reasonable and conservative estimates.

The swelling induced deflections and bending moments obtained from the iterative approach using LPILE were then added to the deflections and bending moments from the WALLAP analyses to give the combined effect.

3.3 *Swelling analyses -VEM*

The second approach used for swelling analyses was a VEM using PLAXIS 2D software. This approach was undertaken to allow comparison with the iterative approach. Shrink-swell index, I_{ss}, values adopted for VEM were reduced by the ratio of in situ suction change and were assumed to decrease linearly from the back of the wall over the assumed lateral extent of swelling. The magnitude of expansion (strain) was assumed to be inversely proportional to the distance from the wall face.

Back analysis of the T2T trial pile wall test was carried out to validate the estimated wall deflections and pile bending moment using this approach. The approach generally underestimated the wall deflections and bending moments by approximately between 0% and 15%, and 15% and 30%, respectively, and is considered to provide reasonable agreement.

3.4 *Design outcome*

For a retained height of 11 m, the design solution comprised cantilever, spaced CFA bored pile walls, typically 900 mm diameter at 1500 mm centres and 20 m long. This wall configuration would not have been possible without the use of unsaturated soil mechanics. By way of comparison, if the retained soil was assumed to be fully saturated from ground level, the wall configuration would have been 1500 mm diameter piles at 1500 mm centres and around 27 m long, to meet the design requirements. This demonstrates that the application of unsaturated soil mechanics has provided significant cost savings to the DUP. The calculated wall deflection and bending moment profiles for both the unsaturated and saturated cases are presented in Figure 6.

The iterative approach over predicts deflection and bending moment, while the VEM approach underestimates the wall behaviour. It is anticipated that the actual wall behaviour due to swelling will lie between these two approaches. The iterative approach was used for design purposes.

4 DESIGN MEASURES TO MINIMISE LOSS OF SOIL SUCTION

The maintenance of a reasonable degree of soil suction is fundamental to the long-term performance of the DUP retaining walls. The following design measures were adopted to maximise the maintenance of soil suction behind the retaining walls:

- shotcrete infill with vertical strip drains were provided to protect the clay between piles and provide a mechanism for groundwater to drain freely (Figure 7);
- the ground surface behind the retaining walls was effectively sealed by the adjacent surface roads. Road cross drainage, in so far as was possible, was designed to fall away from the walls;
- landscaping was facilitated behind retaining walls by the incorporation of tanked planter boxes; and
- inspection pits were incorporated at the base of walls to facilitate observation of seepage as part of the maintenance regime.

5 CONSTRUCTION, INSTRUMENTATION AND MONITORING

All DUP CFA bored pile retaining walls have been installed and bulk excavation for construction of the lowered motorway was underway at the time of writing (January 2019). Wall movements are currently being surveyed during excavation and generally indicate good agreement with estimated excavation induced deflections. Monitoring will be continued until the end of the project defects liability period, which is 5 years after completion of construction. Shape accel array inclinometers within piles and wireless tilt sensors at the top of walls, will be used to provide real-time deflection data at selected wall locations. Wall movement data will be collected via data loggers and transmitted to a data hub using modems. It is to be hoped that some of the instrumentation can be retained by DPTI following the end of the defects liability period to provide valuable data on the long-term performance of the walls and the potential effects of swelling. It is the author's intention to present the measured construction and post-construction horizontal movements of the walls in a future paper.

6 CONCLUSION

Ground conditions at the DUP site consisted of mainly unsaturated clays with hard consistency, which is an ideal condition for retaining wall design using unsaturated soil mechanics.

The results of DPTI's innovative Trial Pile Wall Study for the T2T project demonstrated that design solutions that took advantage of the nature of the unsaturated soils could provide more economical retaining wall solutions than would otherwise have been feasible using saturated soil mechanics. The approach adopted for the DUP facilitated the use of higher design strengths than conventional saturated strengths and provided significant construction cost savings to DPTI.

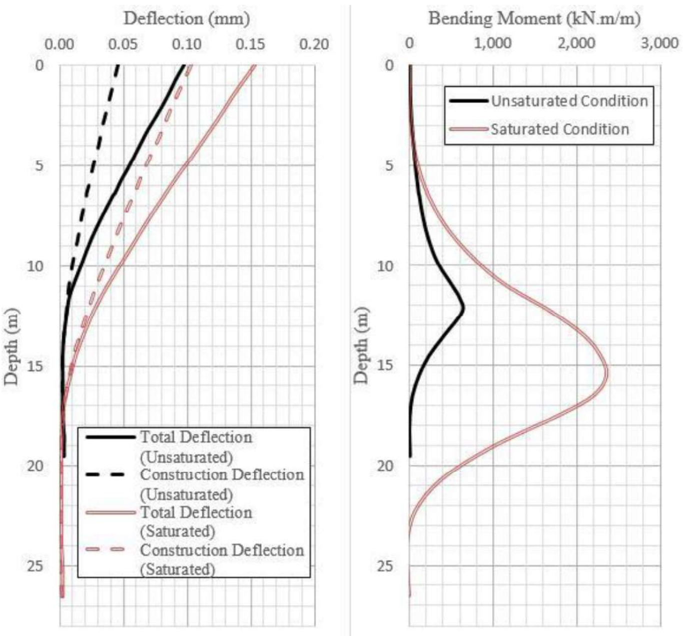

Figure 6. Wall deflection (left) and bending moment (right) profiles

Figure 7. Shotcrete infill with vertical strip drains

Briaud's equation was selected for unsaturated strength estimation, as it was considered to be more representative of the site data and allowed the adoption of higher suction related strengths at lower suctions in design.

Design measures were adopted to maximise the maintenance of soil suction behind retaining walls. If the instrumentation and monitoring regime is retained by DPTI following completion of the defects liability period, valuable data on the long-term performance of the walls and the potential effects of swelling could be obtained.

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REFERENCES

Austroads 2017. *Guide to Pavement Technology Part 2: Pavement Structural Design.*

Briaud, J-L. 2013. *Geotechnical Engineering: Unsaturated and Saturated Soils*. John Wiley and Sons Inc.

CIRIA (Construction Industry Research and Information Association). 2003. *Embedded Retaining Walls - Guidance for Economic Design (C580).*

CIRIA (Construction Industry Research and Information Association). 2017. *Guidance on embedded retaining wall design (C760).*

DPTI (Department of Planning, Transport and Infrastructure). 2014. RN6203 South Road. South Road Upgrade. Torrens Road to River Torrens. *Trial Pile Wall Study*. GSU 1421.

DPTI (Department of Planning, Transport and Infrastructure). 2015. *Design Standard: Retaining Walls.*

Fredlund, D. G. & Rahardjo, H. 1993. *Soil Mechanics for Unsaturated Soils.* John Wiley and Sons Inc.

Goh, S. G., Rahardjo, H. & Leong, E. C. 2010. *Shear strength equations for unsaturated soil under drying and wetting.* Journal of Geotechnical and Geoenvironmental Engineering. April, 136(4), 594 –606.

Kay, J.N. & Avalle, D.L. 1982. *Application of screw plate to stiff clays.* Journal of Geotechnical Engineering Division, Vol. 108, Issue 1, pp 145-154.

Khalili, N. & Khabbaz, M.H. 1998. *A unique relationship for χ for the determination of the shear strength of unsaturated soils*. Geotechnique Vol. 48, Issue 5.

Mair, R.J. 1993. Unwin Memorial Lecture 1992. *Developments in geotechnical engineering research, Application to tunnels and deep excavations.* Proceeding of Institutions of Civil En-gineers, Civil Engineering pp 27-41.

Mitchell, P.W. 2016. *Retaining excavations in unsaturated clay*, Proceedings of Australian Geomechanics Society SA/NT Chapter Seminar. The design of cuttings, revetments and re-taining structures for unsaturated clay.

Pointon, S., Gibbons, P. & Cowan, S. 2018. *Design and construction of cost-effective 60^o revetment walls in unsaturated clay*. 13th Australia New Zealand conference on Geomechanics (ANZ 2019). Australian Geomechanics, Perth Australia.

Woodburn, J. A. & Herraman R. A. 2014. *Revetment Walls for Stiff Unsaturated Clay*. Proceedings UNSAT2014 conference, Sydney.