A Lightweight Soil Nail Retaining Wall in Unsaturated Clay

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ABSTRACT: *The city of Adelaide in South Australia is built on a clay plain running north-south between the Adelaide Hills and the sea. Adelaide has a Mediterranean, i.e. semi-arid, climate causing this clay to be unsaturated and stiff to very stiff when above the watertable. To improve traffic flow on the western side of Adelaide an expressway-standard road, the North-South Corridor, is being built. The 4.5km section of the North-South Corridor from the River Torrens in the south to Torrens Road in the north is referred to as the T2T project. For 2 kilometres the expressway-standard road of T2T runs in a cutting up to 9m deep. The amount of material used in conventional retaining walls, and hence their cost, could be greatly reduced if the shear strength of the unsaturated stiff clay could be estimated with sufficient accuracy for engineering design. Recent developments in unsaturated soil mechanics allow the shear strength of the clay to be determined with sufficient accuracy as long as the suction can be estimated with confidence for the various design conditions, e.g. leaking pipes. Geotechnical engineers in Adelaide have over 50 years of experience in measuring soil suction and estimating suction profiles for varying conditions of drainage. This paper shows how that experience, combined with field measurements, allowed for the design of a cost-effective lightweight soil nail/shotcrete walls for T2T by the successful consortium bidding for this job. The walls have now been under construction for a year and will be completed by late 2018. In this paper the geotechnical investigation for the T2T project and the design of the lightweight soil nail/shotcrete wall are described briefly. The geotechnical investigation showed significant sand lenses occurring in the clay in the southernmost part of the project near the River Torrens. A "toolbox" of soil nail/shotcrete wall designs was developed to cope with the variety of sand lenses. During construction the observational method was used to deal with this soil variability. This required inspection of every section of soil exposed during excavation and selection of an appropriate wall design from the design toolbox. Implementing the observational method proved difficult. This, and other problems prolonged construction, resulting in the walls costing more than originally estimated but still considerably less than conventional walls. This paper concludes with a discussion of the difficulties of implementing the observational method in this project, how these difficulties were overcome, and how they could be avoided in the future.*

KEYWORDS: unsaturated, clay, retaining wall, suction, soil nail, observational method, design guidelines

SITE LOCATION: Geo-Database

The city of Adelaide is built on a plain consisting mostly of clay, running north-south between the Mount Lofty Ranges and the sea on the eastern side of St Vincent Gulf on the southern coast of Australia, as shown in Figure 1(a). To improve transport on the western side of Adelaide the North-South Corridor, an expressway-standard road (shown green in Figure 1(b)) running the full length of the metropolitan area, is to be built. Several sections of the North-South Corridor, from Torrens Road to the River Torrens (T2T, see Figures 2(a) and 2(b) below) and the Darlington Upgrade, are currently under construction. The T2T section of the North-South Corridor is marked with red colour on Figures 1(a) and 1(b).

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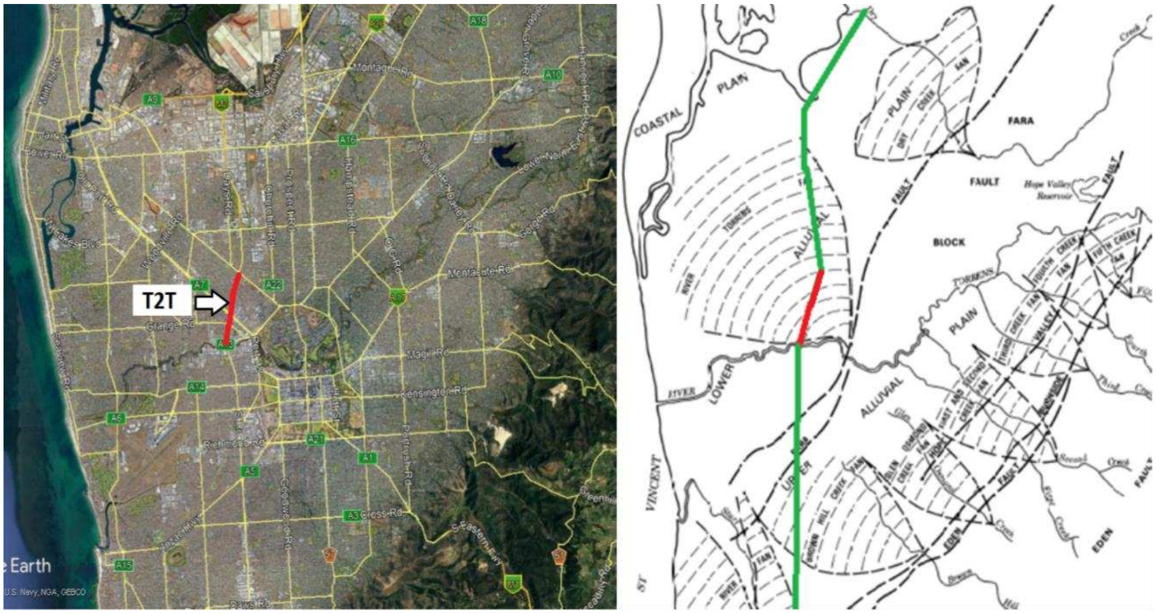
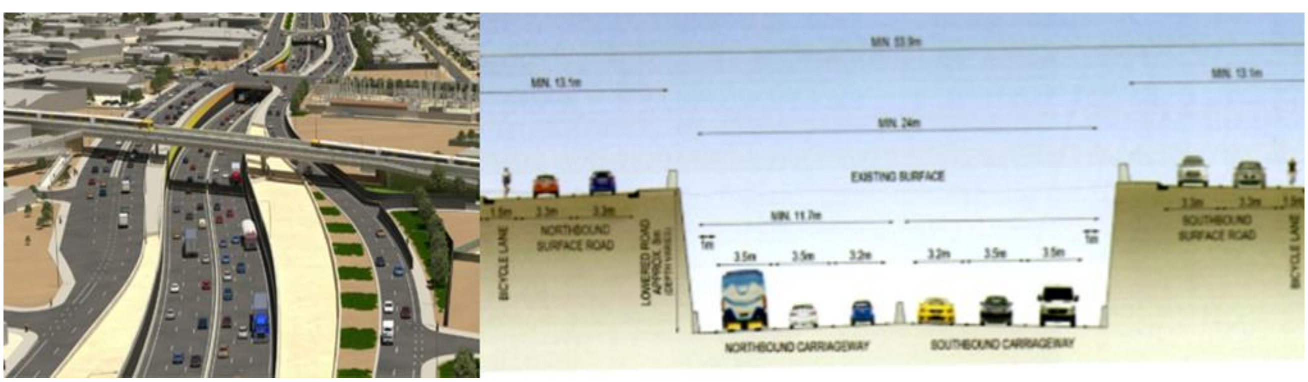


(a) (b)

Figure 1. (a) Location of T2T project in Adelaide (red), (b) Location of North-South Corridor (green)

INTRODUCTION

Both T2T and the Darlington Upgrade include sections of road depressed about 8 to 10 metres below natural surface, requiring revetments and walls to retain the excavations. The Adelaide climate is semi-arid and throughout much of the Adelaide plain the watertable is low. Hence the clay is unsaturated and stiff or very stiff. Unsaturated soil mechanics allow the design shear strength of this clay to be estimated with sufficient confidence for engineering purposes. This shear strength is significantly greater than that formerly used in conventional retaining wall and revetment design when suction is ignored. It allows the use of light-weight walls involving less material usage than conventional retaining walls, giving both environmental benefits and cost savings. The cost savings for the T2T project have been estimated to be about $A20 million. This paper briefly describes the unsaturated soil mechanics considered as well as the geotechnical investigation and field and laboratory testing and analysis needed to obtain the design soil parameters. It also describes briefly the design and construction processes required for these walls.



(a) (b)

Figure 2. (a) T2T artists impression, (b) Schematic cross section.

APPROACHES TO DETERMINE THE SHEAR STRENGTH OF AN UNSATURATED SOIL

There are two main approaches to determine the contribution of soil suction to the shear strength of an unsaturated clay**.**

The Two Stress State Variables Approach

In their book "Soil Mechanics for Unsaturated Soil" Fredlund and Rahardjo (1993) propose the following equation for the shear strength:

$$\tau_f = c' + \sigma_f \tan\varphi + s\tan\varphi^b \qquad (1)$$

where τ_f = shear strength on the failure plane, σ_f = the total stress normal to the failure plane, s = soil suction, $\tan\varphi^b$ = rate of increase in shear strength with increase in soil suction, c'= cohesion and φ = angle of friction. The quantity $c' + s\tan\varphi^b$ is sometimes referred to as an "apparent" cohesion and is function of soil suction.

The Effective Stress Approach

In a presentation at the 8th Australia New Zealand Conference on Geomechanics Khalili and Khabbaz (1999) proposed a relation between shear strength and suction that differs from that of Fredlund and Rahardjo. It adopts Bishop's equation (Bishop 1959) for the effective stress σ' of an unsaturated soil:

$$\sigma' = \sigma + \chi s \qquad (2)$$

where σ is the total stress and χ is the effective stress parameter. For unsaturated soils $\chi < 1$ and $s > s_e$, where s_e is the suction value separating saturated from unsaturated states (i.e. the suction value when air enters the soil if it undergoes drying). For saturated soils $\chi = 1$, $s \leq s_e$ and $s = -u$ (where u is the pore water pressure). The equation for shear strength is of the conventional form:

$$\tau_f = c' + \sigma'_f \tan\varphi'\,' \qquad (3)$$

where σ'_f is the effective stress normal to the failure plane and φ' = effective angle of friction.

The term $c' + \chi s\tan\varphi'$, in which $\chi s \approx \sqrt{s s_e}$, can be considered as the apparent cohesion whose magnitude depends on suction. (Khalili and Khabbaz (1998) showed $\chi = (s/s_e)^{-0.55}$, which leads to the approximation $\chi s \approx \sqrt{s s_e}$). In view of the dependence of strength on suction it is necessary to know the variation of suction with depth, hereinafter referred to as the suction profile. This is described in more detail later. First the geotechnical investigations are detailed.

PRELIMINARY GEOTECHNICAL INVESTIGATION AND DESIGN FOR T2T

A preliminary geotechnical investigation was performed to provide bidding consortia with sufficient information to do a preliminary design and submit a bid. The preliminary investigation was designed to provide sufficient information to enable bidders to determine the wall type (e.g. soil nail/shotcrete or soldier pile) and/or revetment. In the case of T2T the winning consortium decided upon a "lightweight" soil nail/shotcrete wall

Table 1. Comparison of material usage for two projects using soil nail/shotcrete retaining walls (Mitchell 2016).

	T2T Design (clay profile)	Conventional Design (Gallipoli Underpass)
Shotcrete thickness	75mm (typ)	175mm
Shotcrete reinforcement	Macro synthetic fibre (typ)	SL81 mesh
Nail length	4 – 6 (typ)	10m (max)
Nail rows	3	7
Nail diameter	150mm	125mm
Nail spacing	3.0 x 2.5m	1.25 x 1.1m
Nail head	SL81mesh + cogged bar	Anchor plate + nut

Considering the influence of suction in the strength of the clay lead to a greatly reduced thickness of wall and reduced number and length of soil nails compared to when suction influences were ignored. In Table 1 the material usage for the T2T project considering suction is compared to that for the similar Gallipoli Underpass project where suction was ignored. The reduced material usage, applied across the large area of retaining wall for the T2T project (about 27000m^2), translated to an estimated saving of about $A20 million.

THE DETAILED GEOTECHNICAL INVESTIGATION FOR T2T

The geotechnical investigation for T2T comprised field and laboratory testing to obtain information needed for analysis and design using unsaturated soil mechanics.

The field investigation provided the following:

- Sufficient information to determine stratigraphy, especially the variability of the soil profile. Particular attention was given to the identification of clean sand and gravel lenses as well as soil defects, e.g. slickensides, as these affect design and construction.
- Groundwater level.
- Samples for laboratory testing.
- Shear strength profiles from electric Cone Penetration Tests (CPT). Also, thin wall push tube samples were taken from near CPT locations for subsequent measurement of suction to confirm the relationships between shear strength and suction.
- Shear strength profiles from Standard Penetration Tests (SPT) with soil samples taken for measurement of suction and to conduct Pocket Penetrometer (PP) tests.

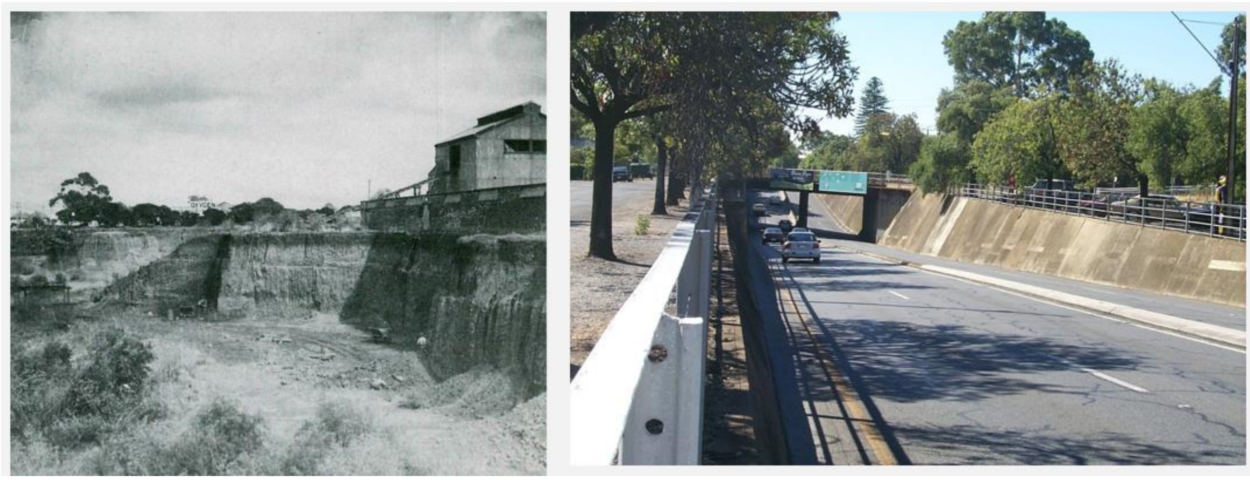
The range of laboratory testing conducted included:

- Determination of particle size distribution and Atterberg limits.
- Determination of the soil-water characteristic curve (SWCC), that is the relationship between moisture content and suction, to enable the suction at air entry to be quantified.
- Consolidated undrained Triaxial tests with measurement of pore water pressure (CUPP) to determine angle of friction.
- Suction measurements in the samples recovered from near the CPT locations and from the SPTs.
- Core shrinkage tests to determine the instability index (I_{pt}) of the clay.
- Oedometer tests to determine the swelling strain and swell pressure of the clay.

SUCTION PROFILES FOR ADELAIDE AND THE T2T PROJECT

For many years suction profiles in Adelaide have been measured and studied, particularly in relation to the design of footings for houses built on reactive clays. Figure 4(a) shows some typical Adelaide suction profiles. In an open area with a deep watertable with typical seasonal suction change or infiltration of surface water, e.g. an irrigated lawn, the suction tends to 981kPa at about 3m depth. For a sealed surface, e.g. under a concrete slab, with a deep water table, the suction tends to 981kPa near the underside of the sealed surface.

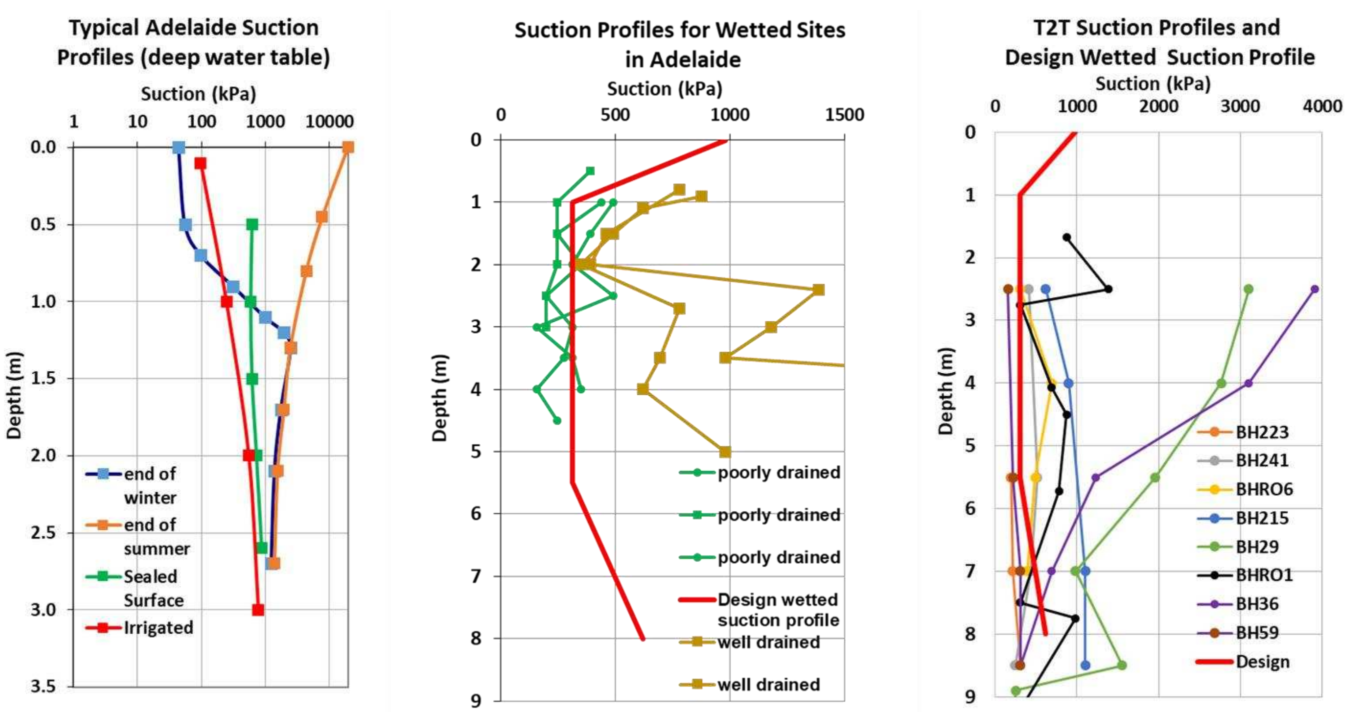
In more recent times engineers in the Geotechnical Engineering Group of the Department of Planning, Transport and Infrastructure (DPTI) of South Australia came to the conclusion that the high suctions in the Adelaide clays resulted in high shear strength and explained why many deep excavations were stable for many years and why lightweight revetments were stable. For example, the near-vertical 9m high faces of the clay quarry of the Hallett Brick Company stood unretained for decades. Also, a 6.5m high revetment of 100mm thick reinforced concrete, inclinded at 2v:1h, has supported an underpass for over a century despite flooding (see Figures 3(a) and 3(b) below, Herraman 2015). It was also noted by DPTI engineers that the presence of defects (e.g. slickensides) in the clay could significantly reduce the shear strength and needed to be taken into account in the design and construction of any retaining structure in unsaturated clay.



(a) (b)

Figure 3. (a) The Hallett Brick Company clay quarry, (b) Underpass at Millswood, Adelaide.

DPTI engineers realised that, if the shear strength due to suction could be quantified sufficiently for engineering purposes, lightweight retaining structures could be used. This would result in large savings in projects such as the North-South Corridor that required large retaining walls. To determine the minimum contribution of suction to shear strength it was necessary to determine a “design wetted” suction profile, i.e. a profile representing the lowest suctions expected to occur in the life of the structure.



(a) (b) (c)

Figure 4. (a) Typical Adelaide suction profiles for deep watertable situation, (b) Suction profiles for sites with surface and subsurface wetting. Design wetted suction profile shown red, (c) Some measured suction profiles for the T2T project and the Design wetted suction profile.

DPTI determined the "design wetted" suction profile using information from three sources:

1. Measured suction profiles at a site that had leaking water pipes and poor drainage
2. Measuring the suction profile near a water-filled trench at a site with good drainage (Woodburn 2014)
3. Modelling with SEEP/W software (Woodburn 2014)

Suction profiles from sources 1 and 2 are shown in Figure 4(b). From these, and source 3, the design wetted suction profile was determined (Woodburn 2014) and is shown in red colour in Figures 4(b) and 4(c). Figure 4(c) also shows typical suction profiles for the T2T project. The profiles vary greatly. The plots in Figure 4(c) in which the suction is approximately 250kPa are from locations where there is infiltration of subsurface water, e.g. from wet sand layers (referred to in Adelaide as perched water), or leaking water pipes and poor drainage. In Figure 4(c) it can be seen that a few suctions are less than the design wetted profile. These suctions mostly arise from perched water that will be drained by the drainage system of the retaining wall, or from leaking pipes that will be repaired.

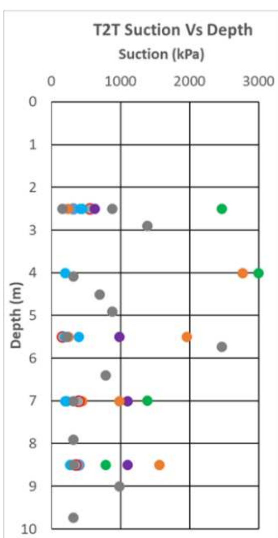
How suction may vary during the project was also considered. At locations in the Adelaide Region with a deep water table, and where the surface is sealed, the suction tends to 981kPa. Say, for example, the suction of the clay retained by a soil nail/shotcrete wall is greater than 981kPa when the wall is built, during the life of the structure the clay may absorb water and swell, push on the retaining wall thereby deforming it and causing items (e.g. luminaires) attached to it to move. For structural design of the wall, and to determine its movement, it is necessary to know the change in suction to reach equilibrium, the Instability Index (I_{pt}) of the clay and it's swell pressure-strain behaviour. This is not discussed in this paper.

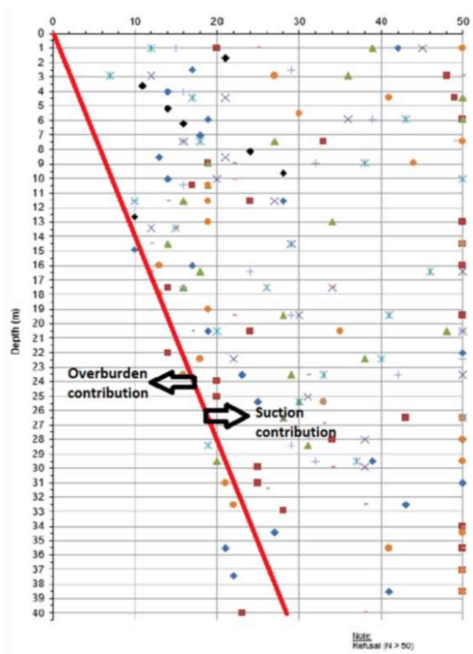
ANALYSIS AND DESIGN

A range of test results were collected. Only those from the SPTs and pocket penetrometers are discussed here.

Interpretation of Data from Standard Penetration and Pocket Penetrometer Tests

Figure 5(a) shows suction values measured in the T2T boreholes. There is a great variation. Figure 5(b) shows SPT blow counts (N values) with depth for T2T. Given the great variation in suction it would be expected that SPT blow counts also would have a similar variation. At the T2T site the groundwater is at 13m depth. In Figure 5(b) it can be seen that below 13m depth the lower bound of blow count increases with depth at a rate of approximately 7 blows per 10m increase in depth. This corresponds to an increase in shear strength increase of approximately 7N, i.e. 49kPa, in 10m depth. An increase of this magnitude would be expected from increasing overburden stress with depth. Blow counts larger than the lower bound values arise from increased strength due to soil suction.

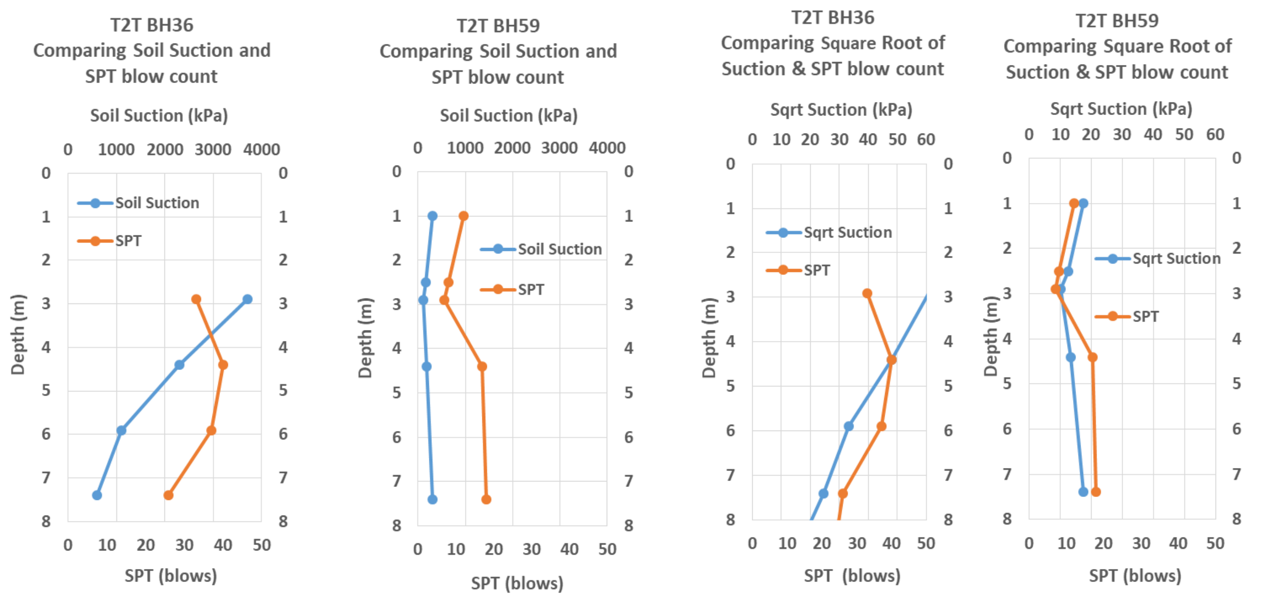




(a) *(b)*

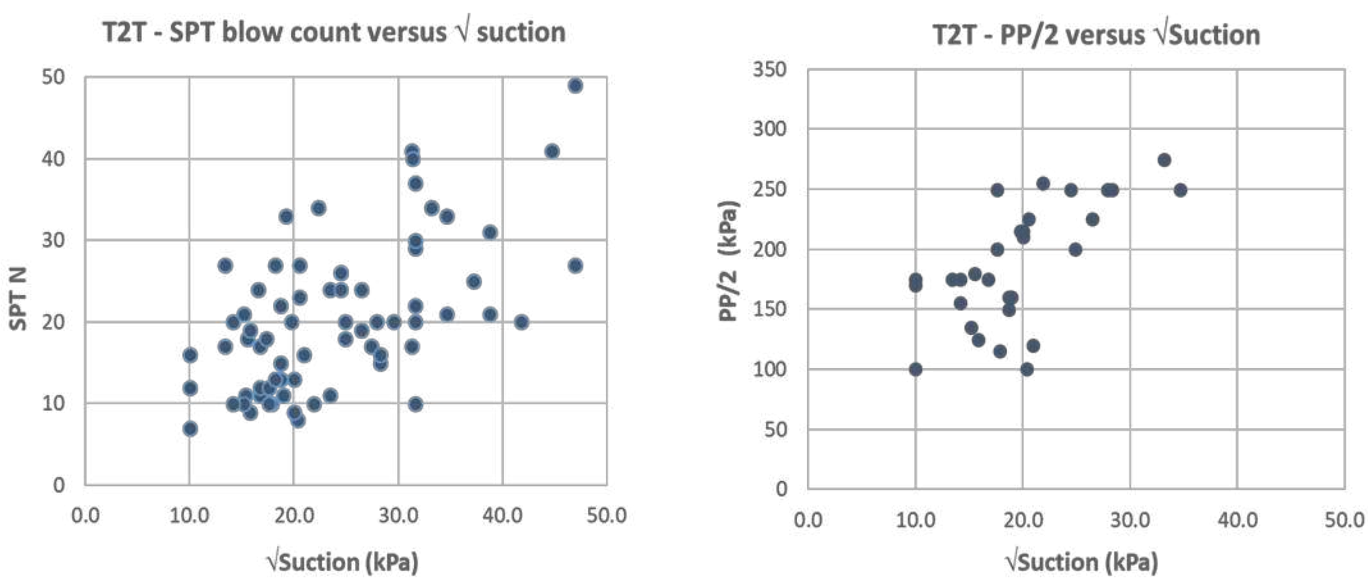
Figure 5. (a) Variation of suction with depth, (b) Variation of SPT blow count with depth.

Figures 6(a) and 6(b) show plots of SPT blow count and suction against depth for two locations on the T2T site, one with high suction and one with low suction. In Figures 6(c) and 6(d) SPT blow count and the square root of suction are plotted against depth. The correlation between SPT blow count and the square root of suction is slightly better than that between blow count and suction. This is in general agreement with the strength relation proposed by Khalili and Khabbaz (1999), in which strength scales with the square root of suction when the soil is unsaturated, that is, the suction is geater than suction at air entry. For the low plasticity clay on the T2T site the suction at air entry was approximately 200kPa.



(a) (b) (c) (d)

Figure 6. (a) Plot of SPT blow count and suction versus depth at site BH36, (b) Plot of SPT blow count and suction versus depth at site BH59, (c) Plot of SPT blow count and square root suction versus depth at site BH36, (d) Plot of SPT blow count and square root suction versus depth at site BH59.



(a) *(b)*

Figure 7. (a) Plot of SPT blow count versus square root of soil suction, (b) Plot of PP/2 versus square root of soil suction.

Figure 7(a) shows a plot of SPT blow count versus the square root of suction. Given the amount of variation in the soil over the site and the nature of the SPT much scatter would be expected. Even so there is a somewhat linear relation between blow count and the square root of suction, again supporting the idea that strength scales with the square root of suction when the soil is unsaturated.

Figure 7(b) is a plot of the pocket penetrometer reading (i.e. PP/2, typically a measure of cohesion) versus the square root of suction Again there is a reasonably linear relation. The foregoing indicates that Equation (3) gives a more accurate estimate of the shear strength of an unsaturated clay than Equation (1).

DESIGN FOR STABILITY

The design method for stability adopted the loading and suction conditions shown in Table 2 below. Typical design software requires values of cohesion and friction angle for every soil layer. For the T2T project, where the soil was a CL clay whose suction varied with depth, the soil can be divided into layers each having a value of cohesion determined from the average value of suction for that layer. The cohesion may be determined using either of the two stress state variables (Equation (1)) or the effective stress (Equation (3)) approaches, however for the T2T project the two stress state variable approach was used. PLAXIS software was used to determine the stability of the wall under the various loads and suction profiles.

Table 2. Loading and suction conditions and factors of safety used for T2T design (Mitchell 2016).

Wall Condition	Assumed Soil & Load Conditions	Factor of Safety (minimum permissible)
Temporary (worst credible) local stability (i.e. wedge failure)	Equilibrium soil suction 981kPa	1.25
Temporary (most probable) global stability	Equilibrium soil suction 981kPa	1.30
Permanent (most probable) global stability	Equilibrium soil suction 981kPa	1.50
Permanent (moderately conservative) global stability	Long Term Wetted soil suction	1.35
Temporary (worst credible) global stability	Wetted + earthquake	1.05
Temporary (worst credible) global stability	Wetted + collision load	1.05

As can be seen from Figure 8, there is significant variability in the soil profile along the T2T alignment, especially in the occurrence of sand layers. Figure 1(b) shows the T2T project to be located in the outwash, i.e. flood, plain of the River Torrens. Flood plains typically have layers of sand and gravel deposited by the river. In this case deposits of clean sand up to a thickness of about 1.5m were found near the river. As can be observed in Figure 8, fewer and thinner deposits of sand were located further from the river.

The variability necessitated the use of the observational method. For this project the designer produced designs (the "design toolbox") for a range of possible soil profiles. These designs typically involve differing soil nail lengths and spacings. The implementation of this during construction of the T2T project is described below.

It is also necessary for the designer to determine wall deflection (i.e. the serviceability limit state) due to change in suction as equilibrium suction is achieved in the soil after completion of construction. This is needed to ensure that movement of items, e.g. luminaires, attached to the wall is within acceptable limits.

As volume change of the clay due to change in suction was expected, the shotcrete was reinforced with polymer fibres rather than steel fibres as there was doubt that the steel fibres could cope with the expected strains. In addition, difficulty was encountered in designing an interface between the soil nail head and the polymer fibre reinforced shotcrete that could cope with movement of the clay without the soil nail head detaching from the shotcrete.

Good drainage is essential to ensure good performance of the wall. The design should incorporate measures to prevent surface water from seeping into the soil near the wall and measures such as strip drains behind the wall and weepholes, to drain water out. The use of weepholes is advised so that locations where water is getting behind the wall can be detected and measures (e.g. fixing leaking pipes) taken to stop the ingress of water and thus avoid excessive deformation of the wall.

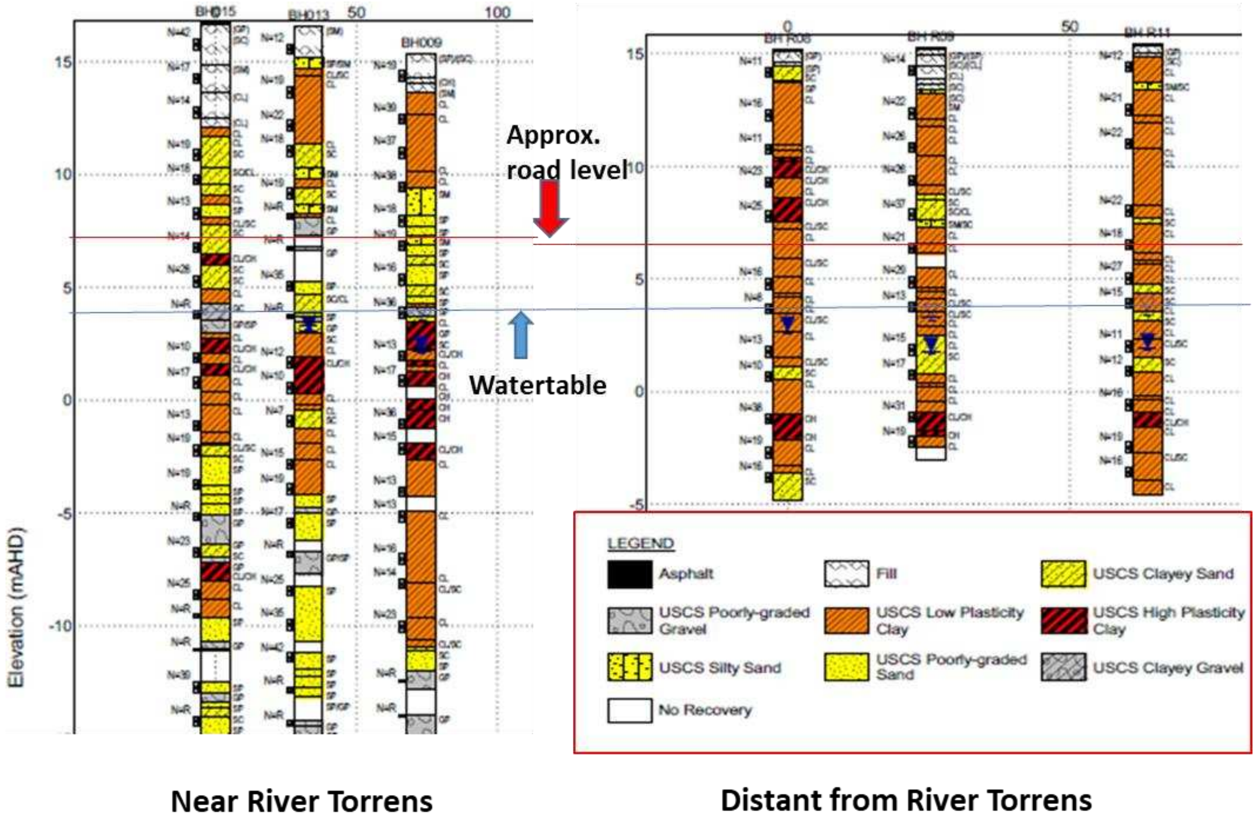


Figure 8. Eamples of T2T soil profiles (URS-W&G 2014).

CONSTRUCTION

Figure 9 shows the stages in the construction of a typical soil nail/shotcrete wall.

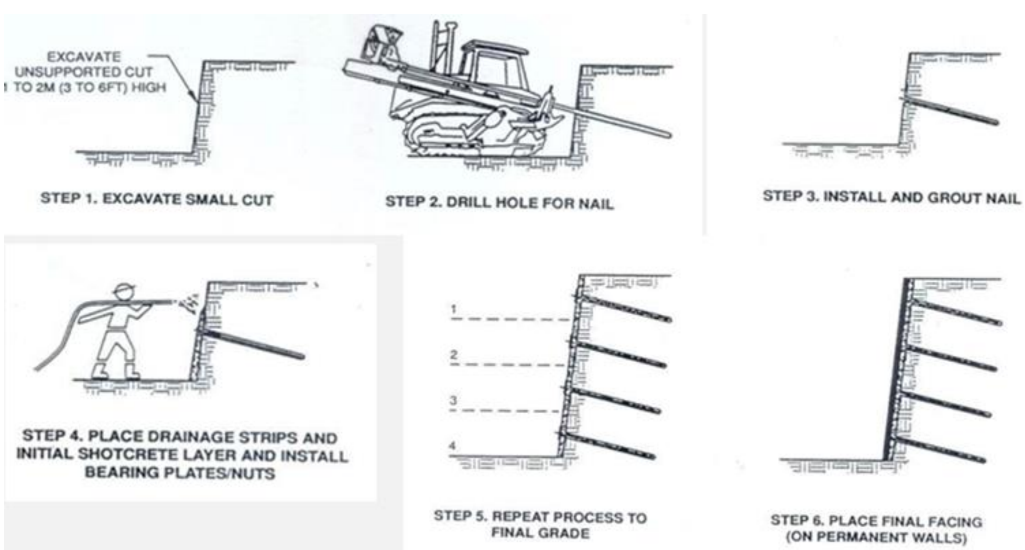


Figure 9. Stages of construction of a conventional soil nail/shotcrete wall (FWHA, 2003).

Use of the observational method to deal with soil variability rendered it necessary to inspect the soil face exposed on each new bench and choose the design appropriate to the soil from the design toolbox before soil nailing and shotcreting could proceed on the bench. This requires a change in staging as shown in Figure 10.

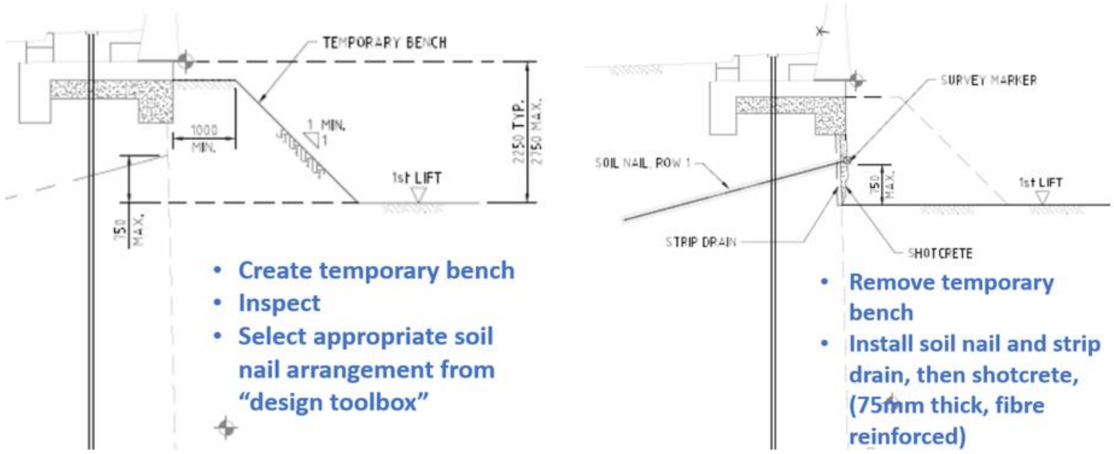


Figure10. Implementing the observational method during construction of a soil nail/shotcrete wall.

In this project construction did not proceed as quickly as expected due to:

- the occurrence of thick layers of clean sand, particularly near the River Torrens
- variation in construction method required to implement the observational method
- lower than expected strength of soil nails.

Where thick layers of clean sand were encountered, or expected to occur, various measures including the use of shallower lifts and temporary soil nails were needed to enable construction to proceed. Figure 11 shows photographs of the wall before and after shotcreting.

Figure 11. Photographs of wall prepared for shotcreting (left) and shotcreting completed with some facing panels installed (right).

CONCLUSIONS

Some of the cost savings promised by the use of significantly less material in the lightweight soil nail/shotcrete wall have not been realised because of the previously mentioned delays arising from difficulty in construction. Notwithstanding this the savings were considerable as are the environmental benefits of using much less material.

The benefit of using unsaturated soil mechanics for design and construction of retaining structures for unsaturated clay can be maximised if the guidance provided in Table 3 below is heeded.

Table 3. Factors influencing choice of retaining structure for unsaturated stiff clay.

ISSUE	WALL TYPE		
	REVETMENT	SOIL NAIL/SHOTCRETE	SOLDIER PILE
Space constraint	Use not indicated, but cheapest option providing there is sufficient space and the clay is uniform and free of defects	OK	OK
Sand layers and/or slickensides	Use problematic due to construction hazard and difficulty.	Use not indicated if frequent occurrence of sand layers and slickensides	Easier to deal with sand layers and slickensides, e.g. by using shallower excavation lifts and/or closer pile spacing
Lower Capability Designer and/or Contractor	Use not indicated due to care needed to avoid hazard during construction	Use not indicated due to difficulty of design and construction	Easier to implement, but still not straightforward. Use of observational method desirable.

ACKNOWLEDGEMENTS

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