SAVING MILLIONS ON RETAINING WALLS AND REVETMENTS FOR DEPRESSED MOTORWAYS IN STIFF UNSATURATED CLAY

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ABSTRACT

In regions where the climate is semi-arid to arid and the watertable is low, clay above the watertable is unsaturated and stiff. Recent improvements in unsaturated soil theory 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 retaining wall and revetment design and allows the use of more light-weight retaining walls. Hence the wall uses significantly less steel and concrete. This leads to environmental benefits and considerable cost savings. This paper describes briefly how to design and build such walls.

1. INTRODUCTION

The city of Adelaide is built on a plain consisting mostly of clay, running north-south between the Mount Lofty Ranges and the sea. To improve transport on the western side of Adelaide the North-South Corridor, an expressway-standard road 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 Figure 1) and the Darlington Upgrade, are currently under construction. Both 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. Recent improvements in unsaturated soil theory 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 retaining wall and revetment design and allows the use of more light-weight walls, giving both environmental benefits (that is, using less material) and cost savings estimated at over $A20 million for the T2T project This paper describes briefly the improvements in unsaturated soil theory, the geotechnical investigation and field and laboratory testing needed to obtain the soil parameters needed for design for unsaturated soil, and the design and construction processes required for these walls.

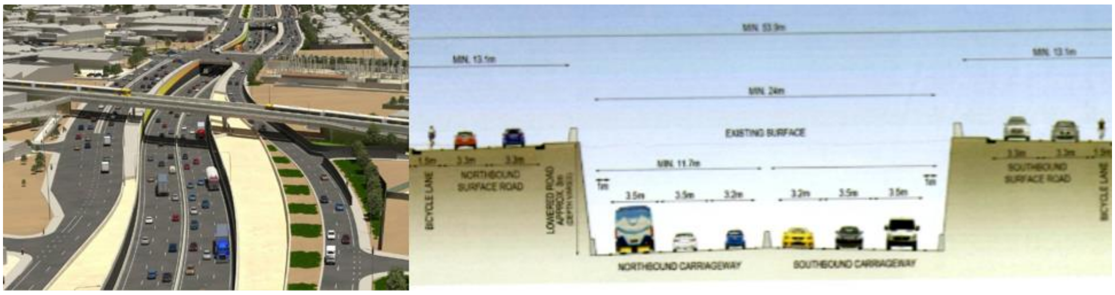

Figure 1: T2T Project, artist's impression & typical cross section

2. RECENT DEVELOPMENTS IN UNSATURATED SOILTHEORY

2.1 Equations for shear strength

In Appendix A it is shown that from Bishop's equation (Bishop 1959) for effective stress (in simplified form)

$\sigma'_f = \sigma - \chi \sigma_w$ (Assume pore are pressure (u_a) = 0 kPa)

and the equation for shear strength

$$\tau_f = c' + \sigma'_f \tan\varphi'$$

when total suction is less than suction at air entry,
shear strength is given by:

$$\boldsymbol{\tau_f = \sigma'_f\, tan\,\varphi' + (c' + \,utan\,\varphi')}$$

Meanwhile, when the total soil suction is greater than suction at air entry (i.e. air has entered the soil), shear strength is given by (see Appendix A):

$$\boldsymbol{\tau_f = \;\sigma'_f\; tan\,\varphi' + (c' + \sqrt{uu_{ae}}\; tan\,\varphi')}$$

where
σ'_f = effective stress on the failure plane
σ = external stress normal to the failure plane

σ_w= pore water pressure
χ = 1 when soil saturated
χ < 1 when soil unsaturated
χ = 0 when soil is dry
u = total suction
c'= cohesion
φ'= angle of friction

The terms $c' + \, u\tan\varphi'$ and $c' + \sqrt{u_w u_{ae}}\, \tan\varphi'$ can be considered as a cohesion, whose magnitude depends on the matric suction.

1.2 The High Shear Strength of Clay in Adelaide & It's Implications

To determine the shear strength of the soil we need its angle of friction, suction at air entry (u_{ae}) and suction. The soil occurring in the Torrens Road to Torrens River (T2T) project is a clay of low to medium plasticity with u_{ae} = 200kPa and φ'= 24degrees. The equilibrium suction (i.e. suction below about 2m depth) is approx. 1000kPa. Substituting these values in the term for cohesion, and putting c'=0 gives 199kPa and explains why deep excavations in this clay are stable when the clay does not have defects such as slickensides. Hence the main function of the retaining wall or revetment is to prevent the clay from drying and cracking and to retain any areas of sand or slickensides. Naturally the wall needs to be well drained to prevent excessive wetting and loss of strength.

Evidence of the strength of unsaturated clay in Adelaide is that the near vertical 9m high faces of the quarry of the Hallett Brick Company stood unretained for decades, and that a 6.5m high revetment of 100mm thick reinforced concrete on an underpass has performed well for over a century, despite flooding (see Figure 2 below).

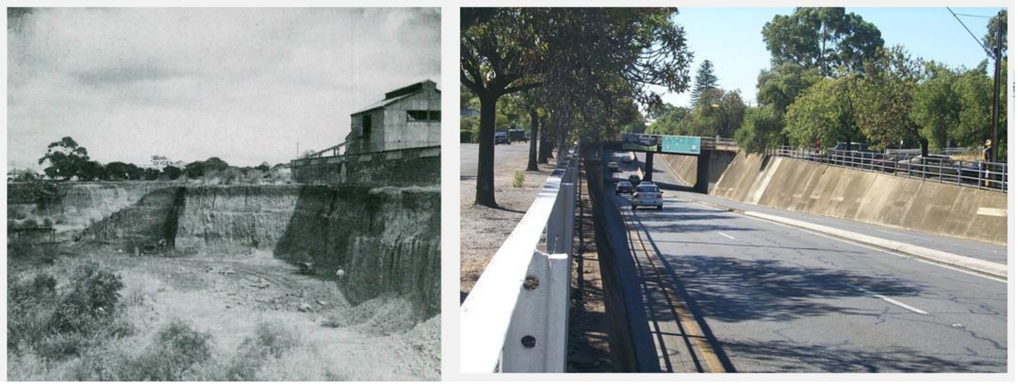

Figure 2: The Hallett Brick Company clay quarry and the underpass at Millswood, Adelaide

1.3 The Design Suction Profile, How to Determine It & How to Use It

In view of the dependence of cohesion, and hence shear strength, on suction, it is necessary to know the lowest values of suction that are likely to occur in the life of the retaining structure, that is, we need to determine a “design” suction profile. In a city it is often leaking pipes and poor surface drainage that wet the soil. The “design” suction profile can be determined by comparing suction profiles of poorly drained and well-drained sites subject to ingress of water. Suction profiles from a poorly drained site are shown in red in the graph on the left in Figure 3 below. Suction profiles from a well-drained site are shown in blue in the graph on the left, together with the 1D design suction profile (green).

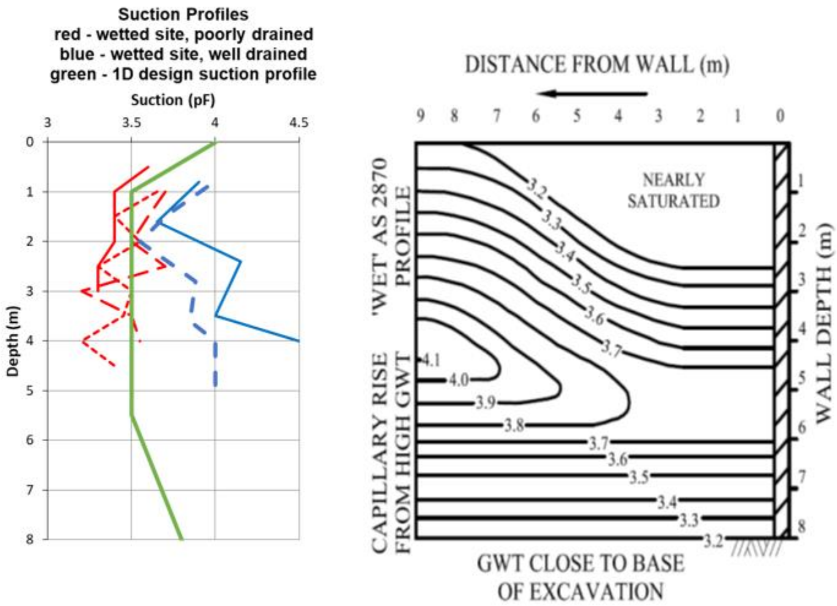

Figure 3: Measured & Design Suction Profiles

The 2D suction profile for the case of groundwater level near the base of the wall is shown on the right in Figure 3 was obtained by modelling with SEEP/W (Geostudio software) and on the basis of experience.

The 2D design suction profile can be used to determine the cohesion at all points in the soil near a retaining structure. The 2D suction profile for a situation where the groundwater level is about 3m below the base of the wall been used to determine the cohesion of the soil layers shown in the XSLOPE (Balaam 1994) model for a revetment in clay.

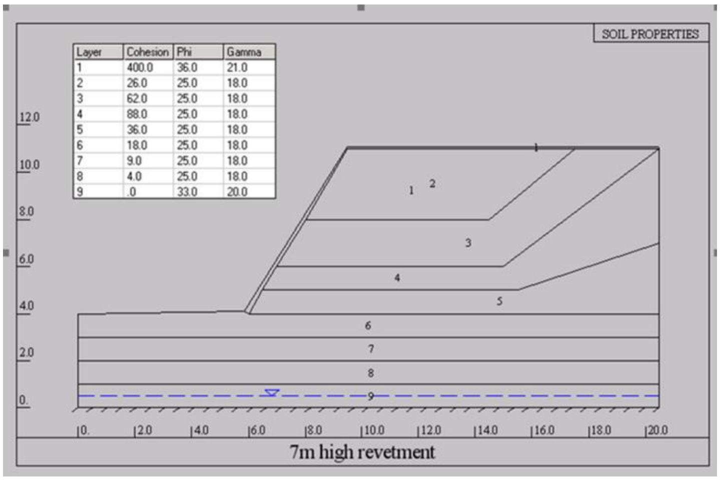
Layer	Cohesion	Phi	Gamma
1	400.0	36.0	21.0
2	26.0	25.0	18.0
3	62.0	25.0	18.0
4	88.0	25.0	18.0
5	36.0	25.0	18.0
6	18.0	25.0	18.0
7	9.0	25.0	18.0
8	4.0	25.0	18.0
9	.0	33.0	20.0

Figure 4: An XSLOPE model with soil layering based on cohesion determined using 2D design suction profile

1.4 The “Trial Pile” Wall

To verify this approach a soldier-pile wall (see Figure 5 below) was built in a low plasticity unsaturated clay using 16m long CFA piles and excavated to 8m depth while monitoring pile deflection. Modelling using FLAC (Fast Lagrangian Analysis of Continua, Itasca 19XX) software showed the wall to be stable on excavation and that it would deflect approx.12mm. This proved to be the case.

Figure 5: The trial pile wall, plan and photograph

To determine how the wall would perform under severe wetting from a shallow water source, 15m long, 300mm wide by 500mm deep trenches were dug one metre behind the walls and kept full of water for several months. During winter the trench was flooded (referred to as deep wetting). During this time pile deflections were monitored and are given in the table below (Woodburn 2014).

Table 1: Summary of pile head deflections during all stages of the trial

Measure	**P11**	**P15**	**P18**	**P30**	**P36**
Maximum deflection on completion of excavation (mm)	8	7	7	5	7
Maximum deflection before wetting (mm)	12	10	10	8	9
Maximum deflection after near surface wetting (mm)	17	37	40	13	29
Maximum deflection prior to deep wetting (mm)	18	42	45	22	35
Maximum deflection after deep wetting (mm)	25	48	55	24	36
Maximum deflection at end of trial (mm)	25	49	55	28	40

2 GEOTECHNICAL INVESTIGATION FOR A RETAINING STRUCTURE FOR UNSATURATED CLAY

Geotechnical investigation and field and laboratory testing is needed to obtain sufficient information to determine whether the use of unsaturated soil mechanics is appropriate for the site and, if so, the choice of wall (e.g. soil nail/shotcrete or soldier pile) or revetment and the soil parameters needed for design for unsaturated soil. The extent of the investigation will depends on the size and complexity of the project.

To be provided by the Field Investigation:

- Sufficient information to determine stratigraphy, in particular the variability of the soil profile. in particular, the occurrence of clean sand and gravel and 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) and Standard Penetration Tests (SPT). Plus thin wall push tube samples near CPT and SPT to obtain samples for measurement suction profiles to confirm the relation between shear strength as measured in the test and suction

Laboratory Testing for:

- Particle Size Distribution & Atterberg Limits
- Soil Water Characteristic Curve (SWCC) to get suction at air entry
- Consolidated Undrained Triaxial Test with measurement of Porewater Pressure (CUPP) to determine angle of friction
- Suction. To determine suction profiles at or near SPT and CPT location
- Instability Index (Ipt) of the clay, e.g. core shrinkage test
- Swell versus pressure of the clay, e.g. oedometer test

3 ANALYSIS & DESIGN

3.2 Concept Design & Use of the Observational Method

The choice whether to use several or all of, a revetment, a soil nail/shotcrete wall or a soldier pile wall, for a project that requires a clay to be retained over a considerable length depends on:

- soil variability, e.g. the frequency of occurrence and extent of slickensides and sand layers
- clay reactivity – it’s hard to design for the soil nail/shotcrete-clay interaction
- willingness and ability of the designer and contractor to implement the observational method to cope with variability of the soil and the willingness of the client to pay for it.

In projects of considerable length there will be variation in soil conditions. This can be dealt with by choosing a wall type suited for the soil conditions, as indicated in the table below, and use of the Observational Method. This method is being used for the T2T project in Adelaide to cope with sand lenses. A soil nail/shotcrete wall is being used for this project. In this case, use of the observational method requires the designer to produce designs (the “design toolbox”) for various thickness sand lenses. These designs typically involve differing soil nail length and spacing. The implementation of this during construction of the T2T project is discussed in Section 5 below on construction.

It is also possible to implement the observational method very conveniently if Continuous Flight Auger (CFA) piles are being used for a soldier pile wall. During installation of CFA piles auger torque is monitored. This torque is much greater in stiff clay than in sand, hence records of torque versus depth can be used to determine location and approximate thickness of sand layers. Table 2 summarises factors influencing choice of retaining structure.

Table 2: Factors influencing choice of retaining structure for unsaturated stiff clay

ISSUE	REVETMENT	SOILNAIL/SHOTCRETE	SOLDIER PILE
Space constraint	Takes more space	OK	OK
Sand & slickensides	Not indicated due to construction danger	Not indicated if frequent occurrence of sand layers and slickensides	Easier to deal with sand layers and slickensides, e.g. by using shallower lifts
Lower Capability Designer and/or Contractor	Not indicated due to care needed to avoid danger during construction	Not indicated. Design difficult and observational method needed	Easier to implement, but still not straightforward. Observational method needed

3.3 Design

The design method typically is to use modelling software such as PLAXIS to determine the stability of the wall under various loads and using the design suction profile to determine a soil layering based on cohesion, i.e. Ultimate Limit State (ULS) conditions. In situations where there is significant variability in the soil profile (e.g. thick sand lenses) and the observational method is being used, it is necessary for the designer to produce designs (the “design toolbox”) for a range of possible soil profiles

It is also necessary for the designer to determine wall deflection (i.e. 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.

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.

4 CONSTRUCTION

Figure 6 shows stages in the construction of a typical soil nail/shotcrete wall.

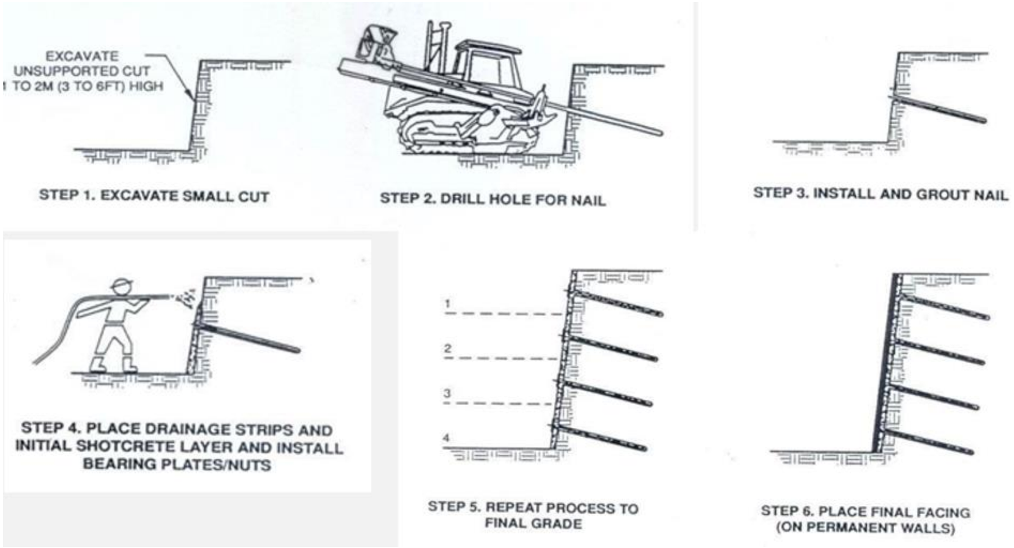

Figure 6: Stages of Construction of a soil nail/shotcrete wall

If the observational method is being used it is necessary to change the staging, as shown in Figure 7, to allow time for inspection of the exposed face and selection of a suitable soil nail arrangement from the design toolbox.

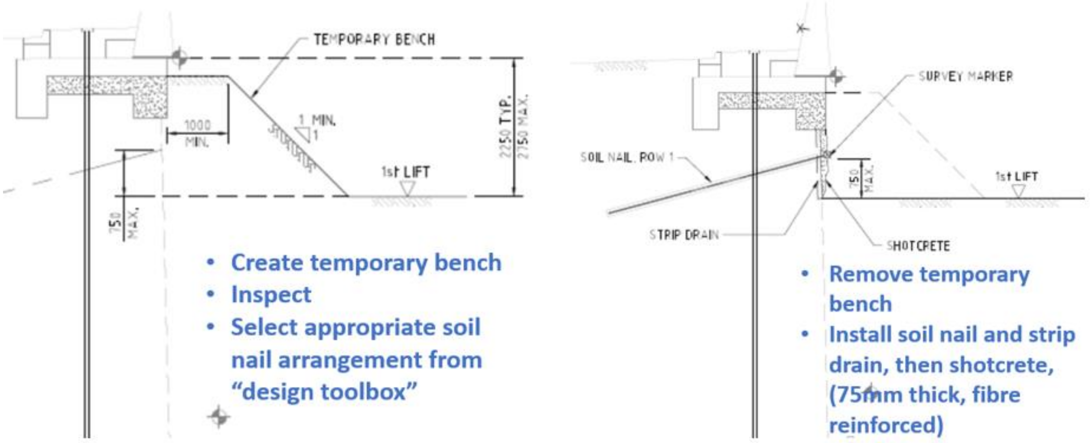

Figure 7: Implementing the observational method during construction of a soil nail/shotcrete wall

5 SUMMARY AND CONCLUSIONS

A better understanding of the behaviour of unsaturated clay leads to the design of lighter-weight retaining walls and revetments. Building these walls requires more care owing to the need to use the observational method. All this is not easy but it has environmental benefits, it saves money and can help you win jobs.

6 ACKNOWLEDGMENTS

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APPENDIX A

Equations for Shear Strength of an Unsaturated Clay

Bishop's equation for effective stress (in simplified form)

$$\sigma'_f = \sigma - \chi \sigma_w$$

where

σ'_f = effective stress on the failure plane

σ = external stress normal to the failure plane

σ_w= water pressure
$\chi = 1$ when soil saturated
$\chi < 1$ when soil unsaturated
$\chi = 0$ when soil is dry

When total suction is less than suction at air entry
The soil is saturated and $\chi = 1$. Bishop's equation becomes:

$$\sigma'_f = \sigma + u \qquad (1)$$

Where u = total suction

Shear strength is given by:

$$\tau_f = c' + \sigma'_f \tan\varphi'$$

Where $\varphi'$is the angle of friction

Substituting from Eqn (1) gives

$$\tau_f = c' + (\sigma'_f + u)\tan\varphi'$$

This can be written:

$$\boldsymbol{\tau_f = \sigma'_f \tan\varphi' + (c' + u\tan\varphi')}$$

The term $c' + u\tan\varphi'$ can be considered as a cohesion whose magnitude depends on suction

When total soil suction is greater than suction at air entry
(I.e. air has entered the soil)

Khalili and Khabbaz (1999) showed $\chi \sim (u/u_{ae})^{-0.55}$

Where u_{ae} is the suction at air entry

To a good approximation $\chi = \sqrt{\frac{u_{ae}}{u}}$

Substituting in Bishop's equation and the equation for shear strength and rearranging gives:

$$\tau_f = c' + (\sigma'_f + \sqrt{(uu_{ae}})\tan\varphi'$$

This can be written as:

$$\boldsymbol{\tau_f = \sigma'_f \tan\varphi' + (c' + \sqrt{uu_{ae}} \tan\varphi')}$$

The term $c' + \sqrt{uu_{ae}} \tan\varphi'$ can be considered as a cohesion whose magnitude depends on suction.