INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

Numerical Modeling of Piled Retaining Wall in Unsaturated Adelaide Clays

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ABSTRACT: Unsaturated clays found in the Plains of Adelaide, South Australia, are typically stiff-to-hard and can exhibit high shear strength due to very high suction. Such suction hardening behavior allows deep vertical cuttings to stand unsupported for significant periods of time. It is evident, from previous studies, that unsaturated soil mechanics is particularly relevant to the design of earth structures in South Australia because of its semi-arid climate. The South Australian Government is currently constructing a 4 km section of non-stop roadway, featuring 3 km of a depressed motorway to a maximum depth of 8 m below street level. In the early design and planning stages of the project, various retaining wall options were considered. Cantilever soldier piles were constructed adopting varying diameters and center-to-center spacings, as part of a full-scale field trial that was undertaken during the design phase. This study examines the use of numerical methods for stability analysis of deep cuttings, using the finite element method to model the performance of the piled retaining walls with different design configurations.

1 INTRODUCTION

Unsaturated clays that underlie much of the Adelaide Plains in South Australia are typically stiff-to-hard and can exhibit high shear strength due to very high suction. Such suction hardening behavior allows deep stable vertical cuttings to stand unsupported for significant periods of time. A local example of a stable earth structure that has remained largely unsupported for more than 100 years is the Millswood Underpass in metropolitan Adelaide, which is a 6 meter deep cutting, with 2V:1H side slopes of and lined with a lightly reinforced, 100 mm thick concrete slab. A review by Kaggwa et al. (2010) studied the long-term stability of the Millswood Underpass using coupled seepage analysis and the limit equilibrium method. By evaluating the variations in the factor of safety (FoS) and using more than 120 years of climate data, they concluded that the slope is very stable, even in extreme cases, such as flooding and pipe leakage. The Kaggwa et al. (2010) study reinforced the view that unsaturated soil mechanics is particularly relevant to the design of the earth retaining structures in South Australia because of its semi-arid climate.

The South Australian Department of Planning, Transport and Infrastructure (DPTI) is currently delivering the Torrens Road to River Torrens (T2T) Project, which includes a 4 km section of non-stop roadway on South Road between the suburbs of Torrensville and Croydon Park, 3 km of which features a depressed motorway to a depth of 8 m below street level. In the early design and planning stages, various retaining wall options were considered for the section of depressed motorway and the associated access ramps. Cantilever soldier pile walls, consisting of different diameter piles and center-to-center spacings were assessed and a full-scale field trial was also undertaken during the design phase. One of the options that was examined was a wall consisting of 600 mm diameter piles at a center-to-center spacing of 1.05 m. These trial cantilever soldier pile walls were constructed in deep alluvial clays, which are described as silty and sandy clays of low-to-medium plasticity. This is consistent with published information from the general area and sediments that have been washed down from the Adelaide Hills and deposited over the lower outwash plains of the Adelaide metropolitan area.

The present study seeks to examine the use of a coupled analysis to estimate the deflections of the soldier pile wall in a range of different cases. An illustration of the numerical modeling undertaken is shown in Figure 1. The 600 mm diameter by 16 m long continuous flight auger (CFA) piles at 1.05 m center-to-center spacings are modelled in a half-space. The top half of the pile wall retains the soil, whilst the other half extends below the water table to a depth of 16 m below the ground. The groundwater flow in both the saturated and unsaturated zones was analysed using *SVFlux* (SoilVision System Ltd., 2013) which is based on the Richards (1931) equations. Adelaide climate data for an average year were used for the seepage analysis, allowing soil suction profiles at various times of the year to be determined.

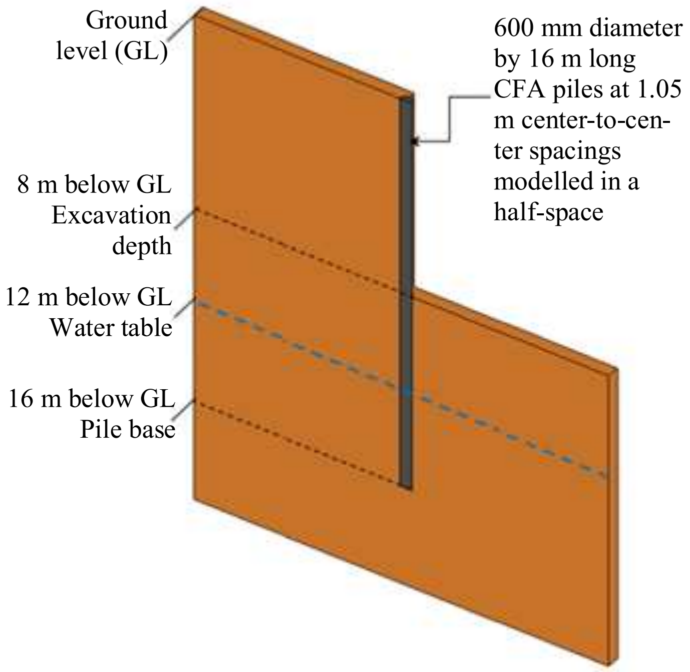

Figure 1. 3D modelling of the soldier pile wall.

2 UNSATURATED SOIL MODELLING

2.1 *Unsaturated soil properties*

To model water flow in the unsaturated zone, the soil-water characteristic curve (SWCC) must be determined. To obtain the SWCC, two types of laboratory tests were undertaken, namely unsaturated triaxial testing up to 500 kPa matric suction, and dewpoint potentiameters (WP4 and WP4C) for higher suctions. The data were then fitted using the Fredlund and Xing (1994) semi-empirical equation, and the adopted SWCC is shown in Figure 2.

The soil properties that were determined from the laboratory tests and adopted in the *SVFlux* and finite element (FE) package, LS-DYNA (Livermore Software Technology Corporation, 2017), are summarized in Table 1.

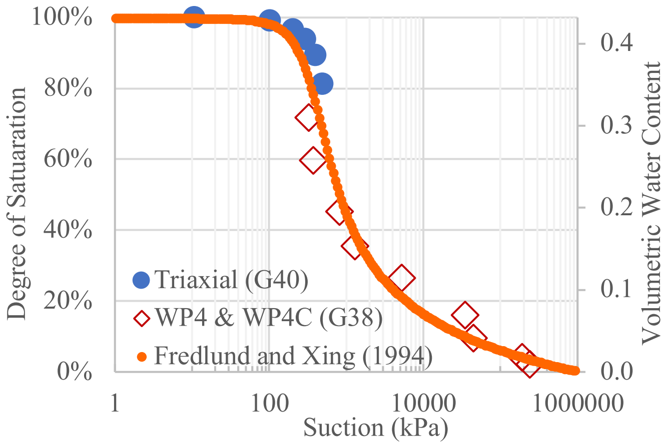

Figure 2. The adopted SWCC.

Table 1. Summary of measured soil properties.

Soil properties	Adopted values
Specific gravity, G_s	2.63
Poisson ratio, v	0.3
Porosity, n	43.2%
Void ratio, e	0.761
Dry density, ρ_d	1,494 kg/m^3
Effective shear strength: c' and ϕ'	0 kPa and 35°
Air entry values	200 to 225 kPa
Permeability coefficient, K_{sat}	8.64×10^{-4} m/day or 1.0×10^{-8} m/s
Minimum unsaturated permeability coefficient, K_{min}	

2.2 *Climate data*

Adelaide has a semi-arid climate with mild to cool winters with moderate rainfall, and warm to hot summer with very little precipitation. The average annual rainfall is approximately 550 mm. Adelaide climate data, which consists of maximum and minimum relative air humidity (shown in Figure 3), daily temperature (Figure 4), rainfall and potential evaporation (Figure 5) over 420 days (from March 2015 to April 2016) were used in this study.

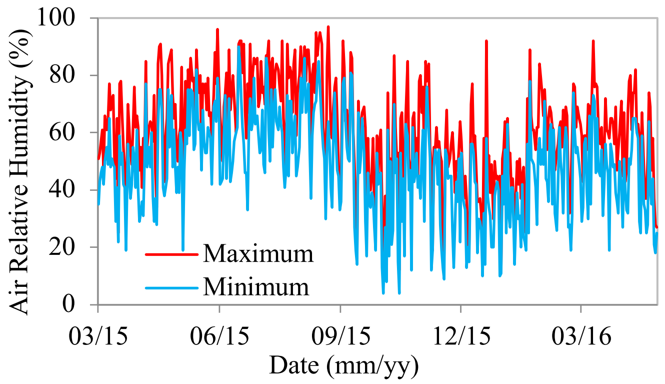

Figure 3. Air relative humidity recorded from March 2015 to April 2016.

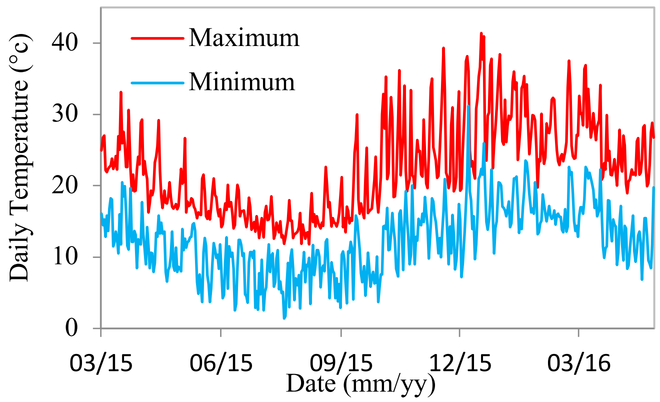

Figure 4. Daily temperature data.

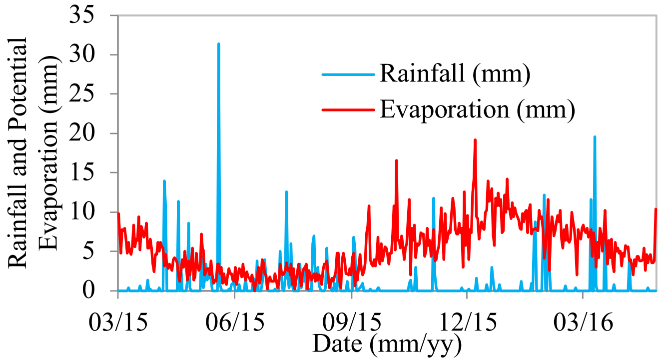

Figure 5. Daily rainfall and potential evaporation data recorded in Adelaide from March 2015 to April 2016.

2.3 *SVFlux modeling results*

Three different cases were studied in this paper: (a) pre-excavation, (b) post-excavation, and (c) pipe-leakage. For the pre-excavation case, the *SVFlux* results are shown in Figures 6 and 7. Figure 6 shows the variations of matric suction with time at different depths down to 4 m below the ground surface. It can be observed that the matric suction within the first meter below ground fluctuates widely and is very sensitive to daily climate and seasonal changes. The matric suction at the surface decreases whenever there was a significant daily rainfall event, and increases when the daily temperature rises. The matric suction within the first 4 m below ground trended lower during the autumn to winter months (March – August) and rose in the spring to summer months (September – February). Figure 7 shows the soil profiles at the end of summer and winter. It also shows the lowest (~120 kPa [pF 3.1]) and highest (~5,170 kPa [pF 4.7]) matric suction experienced over the 420 days.

For the post-excavation and pipe leakage cases, the *SVFlux* results are presented in Figures 8 and 9, respectively. For the post-excavation case, it is assumed that all surfaces are unsealed and exposed to climatic conditions. It is evident that the summer and winter profiles are very different (Figure 8), as well as the leaking services have significant effects on suction profiles (Figure 9).

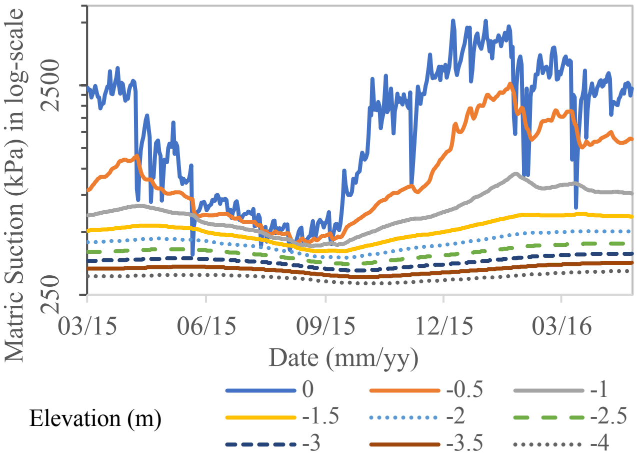

Figure 6. The variations of soil suctions at various depths prior to excavation.

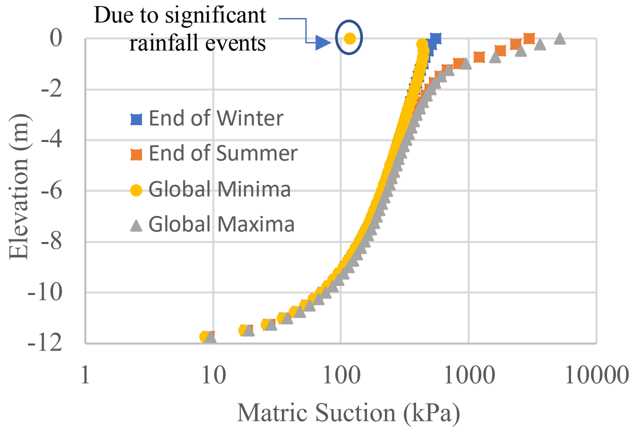

Figure 7. Variation of soil matric suction with depth at end of summer and winter, as well as for extreme scenarios.

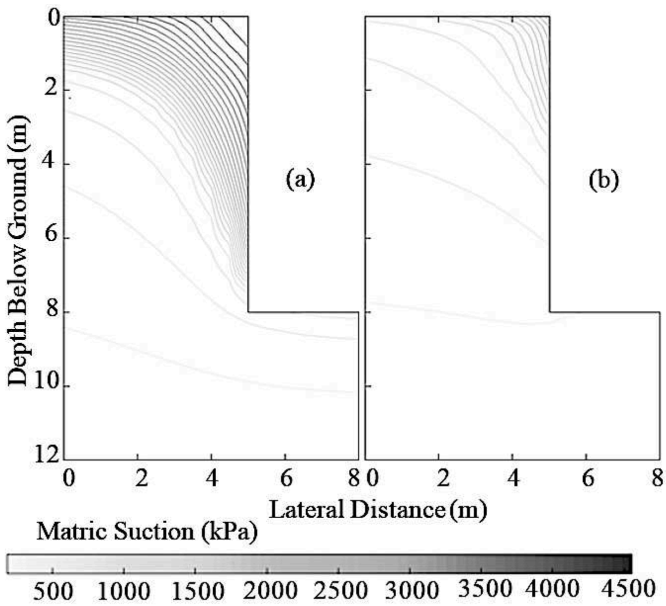

Figure 8. Soil suction profiles for post-excavation: (a) at the end of summer; (b) at the end of winter.

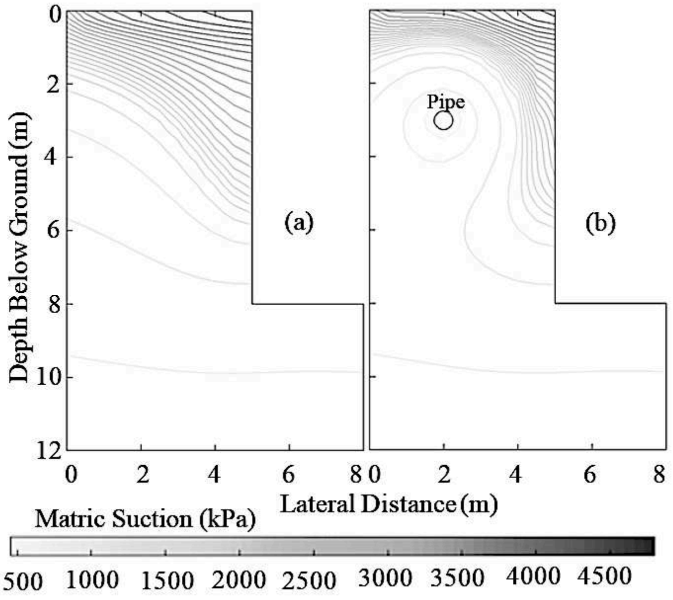

Figure 9. Soil suction profiles for leaking pipe case: (a) no leakage; (b) leaking pipe.

2.4 *Unsaturated shear strength behavior*

Shear strength (τ) of an unsaturated soil can be determined from $\tau = c' + [(\sigma - u_a) + \chi\ (u_a - u_w)]\ \tan\phi'$, where $(u_a - u_w)$ is matric suction, c' and ϕ' are the effective cohesion and friction angle, respectively. In this study, the estimated shear strength increment due to suction is determined using the relationship between χ and suction ratio developed by Khalili and Khabraz (1998):

$$\chi = \left[\frac{(u_a - u_w)}{(u_a - u_w)_b}\right]^{-0.55} \qquad (1)$$

where $(u_a - u_w)_b$ is the air-entry value. The air-entry value determined from the particular soil samples used in this study varied between 200 and 225 kPa, and a conservative value of 200 kPa is adopted. The contribution of suction to the shear strength ($\tau - \tau_0$, where τ_0 is shear strength of fully saturated soil) is shown in Figure 10. The effective shear strength parameters (c' and ϕ') for fully-saturated soil were assumed to be zero and 40°, respectively, which were, again, conservative estimates for over-consolidated clays.

2.5 *Stability analysis – excavation without support case*

To demonstrate the effect of unsaturated behavior on the stability of an 8 m vertical cut in Adelaide soils, a coupled stability analysis is carried out in 2D using both *SVSlope* (SoilVision, 2009) and *SVFlux*. The analysis demonstrates that a very stable, unsupported vertical cut is possible with a high FoS varying from ~5.0 to ~6.3 (Figure 11) over the study period, and the variation of the FoS is coupled to the variation in suction due to climatic fluctuations.

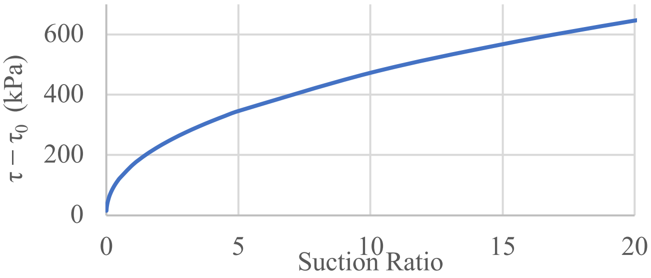

Figure 10. $\tau - \tau_0$ versus suction ratio.

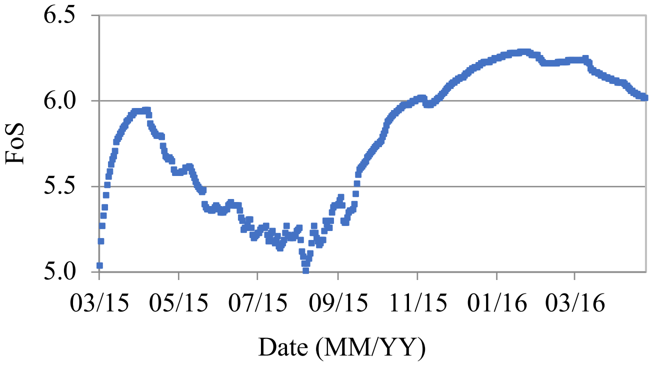

Figure 11. Results of stability analysis using *SVSlope* (excavation without support case).

2.6 *Stability analysis – excavation without support case and leaking services*

Excessive water ingress from undetected leaking services can reduce the stability of the vertical cut. In this paper, it was assumed that the hypothetical leak is located 3 m below the street level and 3 m behind the face of the vertical cut. A 4.5 m pressure head leak is adopted, slightly below the overburden pressure, such that no water spout would occur (from below the surface to the ground surface), and it was assumed that the leak was left undetected for several months. Due to the low permeability of the soil, a leaking pipe would require an extended period (weeks or months) to allow water infiltration into the surrounding soil and to have maximum influence on the stability of the cut. It was also assumed that leakage occurred post-construction, hence a uniformly distributed loading of 10 kPa was applied to the top of the vertical cut and 5 m away from the cut, to simulate traffic live loading. The results showed that the FoS reduced steadily from ~6.0 in early March when the leak commenced, to ~2.0 in August/September, coinciding with the end of winter and the leak remaining undetected for a period of 6 months (Figure 12). As Adelaide receives most of its rainfall in winter, it is possible that the FoS could decrease further if the leak continued for another year into a winter that was wetter than the typical year that was modelled. However, it could be argued that it is highly unlikely that such a leak would continue undetected for such a long period of time.

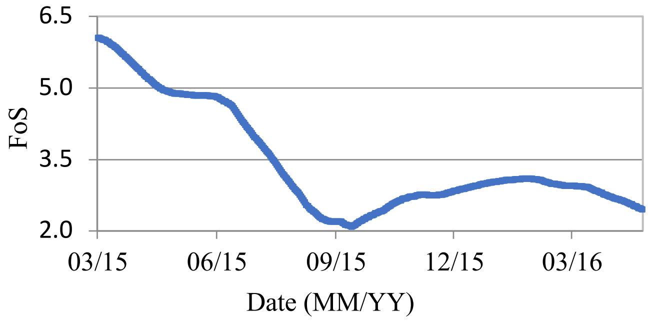

Figure 12. Reduction of FoS due to leaking services.

3 MODELING SHORT-TERM PERFORMANCE OF SOLDIER PILE WALL

As mentioned, the short- and long-term performances of the proposed CFA pile wall were studied in a field trial undertaken by DPTI. Deflection data were obtained using surveying technique at different times and situations (e.g. pre- and post-excavation, after significant rain, and artificial wetting). This is a complicated soil-structure interaction problem. Many methods have been proposed and trialled to estimate the pile deflections. Due to time and space constraints, this paper focuses only on the short-term performance (deflection after excavation case) of the pile retaining wall using numerical modelling. The constitutive models used in this paper and their inputs are discussed and the results are presented in the following sections.

3.1 *Properties of concrete pile*

Concrete is a quasi-brittle material with low capacity deformation under tensile strength. Micro-cracking develops in matrix-aggregate composites, like concrete, when the tensile stress exceeds the tensile strength. This softening process needs to be considered when designing a concrete structure that satisfies both ultimate and serviceability criteria. In this paper, the reinforced concrete pile was modeled using the Winfrith concrete model in LS-Dyna. The Winfrith concrete model was developed by Broadhouse & Neilson (1987), and Broadhouse (1995) over many years and has been validated against experimental data. This model is a smeared crack (sometimes known as pseudo crack), smeared rebar model, implemented in the 8-node single integration point continuum element. This type of model treats the cracked solids as a continuum and describes the softening behavior in terms of a stress-strain relationship. It can generate an additional binary output database containing information on crack locations, directions, and widths. The inputs for the concrete components are summarized in Table 2.

Table 2: Summary of concrete properties.

Soil properties	Input Values
Poisson ratio, v	0.15
Characteristic compressive strength at 28 days, f_c	40 MPa*
Initial tangent modulus, $E_c = 5000 \times \sqrt{f_c}$	31,623 MPa
Density, ρ_d	2,400 kg/m^3
Maximum aggregate size	10 mm

* According to concrete supplier's production log.

Each 600 mm diameter pile comprised six 24 mm diameter Grade 500N steel reinforcing bars. The actual engineering properties of these rebars were not made available to this study, therefore typical values found in the literature were used. According to Australian Standard *AS 4671: Steel Reinforcement Materials*, a Grade 500N bar must have a yield strength of 500 MPa as lower (minimum) characteristic value, and 650 MPa as an upper value. The Young's modulus of steel rebar was taken to be 200 GPa. The tensile strength was assumed to be 1.08 times the yield strength and the ultimate elongation at maximum force prior to the bar failing was assumed to be 5%. The strain hardening modulus of the rebar was estimated to be 842 MPa.

3.2 *Properties of soil*

In this study, it was assumed that the soil mass behind the pile wall had uniform geotechnical properties, as shown in Table 1. However, because of the variations of soil suction, the soil mass above the groundwater level was divided into 24 layers, and each of these layers was 0.5 m thick and had different moisture content, bulk unit weight and unsaturated shear strength. For this short-term analysis, because the soil had very low permeability, it was appropriate to assume the moisture content of the soil mass for pre- and post-excavation cases, within a short period of time, were almost constant. The excavation for the field trial took place from late October through to late November. Therefore, the soil (matric) suction profile over that time period was obtained from *SVFlux*, and was used to generate inputs for the stability analysis using *SVSlope*.

3.3 *Validations of numerical results against field results*

Figure 13 compares the results of the numerically simulated pile deflections with those measured in the field trial after excavation. The results showed that the numerical model provided almost the same deflection (approximately 10.5 mm) at the top of the pile as that measured. The numerical simulation can be further improved by using measured values of the concrete strength and reinforcing bar properties, as well as using variable site conditions rather than an idealised one.

By using the Winfrith concrete model, which accounts for softening due to cracking, a more realistic deflection profile was obtained when compared to that from a simple elastic constitutive model. If latter were used, although it requires far fewer inputs, it generally yielded lower deflection values, as well as an unrealistic deflection profile, and a somewhat stiffer response.

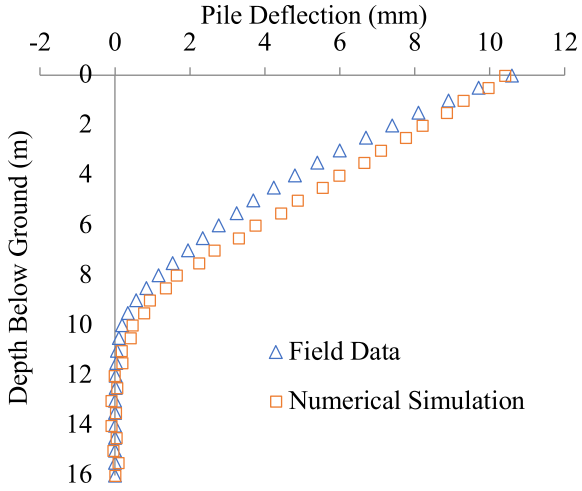

Figure 13. Numerical modeling results compared against field-measured data (after excavation case).

3.4 *Future research*

To study the long-term serviceability performance of the pile walls, the effects of swelling pressure (due to changes in soil moisture content and volume) should also be incorporated into the analysis. It will be useful for determining the additional deflections and moments that would occur during extreme wetting events behind the pile walls, such as leaking services or short-term flooding, and to evaluate whether the piles had been overstressed. The model may also be used to predict the soil moisture or suction variations that lead to changes in soil volume and shear strength and to quantify the extents as well as the effects of those changes, and to relate these to the measured deflections in the field.

4 CONCLUSIONS

This study demonstrated the use of numerical analyses for determining the variations in suction profiles of a vertical cutting resulting from climatic variations and leaking services. Through coupled analysis (seepage in unsaturated soils and stability analysis using the limit equilibrium method), the variations of the factor of safety of the vertical cutting in unsaturated Adelaide clays with the suction changes can also be obtained, and it is evident that the vertical cut can stand unsupported in Adelaide clays due to its semi-arid climate. By adopting an accurate constitutive model for the concrete piles, the FEM yielded results that are in good agreement with measurements obtained from a full-scale trial of the retaining wall. This study confirms that accurate predictions of the stability of a vertical cut and the performance of pile walls are possible if appropriate numerical methods are adopted.

5 ACKNOWLEDGEMENTS

The authors sincerely thank Kevin Farries and Gary Bowman from the School of Civil, Environmental and Mining Engineering at The University of Adelaide for their technical support during the project. Richard Herraman, John Woodburn and the geotechnical team from DPTI are also acknowledged for providing data from the full-scale retaining wall trial. The authors would also like to thank the following Honours Research students who have contributed to the WP4 and WP4C test results referred to within this paper: Justin Bonney, Sachit Desa, Henry Jensen and Caillin Millar.

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