Field performance of a deep cut and cover excavation in Singapore old alluvium designed based on advanced soil testing

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ABSTRACT

The Old Alluvium (OA) occurs extensively to the east of the island and is believed to be deposited from a braided river system. Site observations during the construction of underground spaces in Singapore have shown that excavations in the OA resulted in measured retaining wall deflections that were significantly less than design predictions. This highlighted the need to review the OA geotechnical modelling for excavations, including the derivation of soil parameters to best represent the observed behavior. A section of a proposed Singapore Mass Rapid Transit (MRT) alignment run mainly through the OA and presented the opportunity to further investigate this formation. This paper summarizes the site investigation works carried out, including laboratory and in-situ measurements of small strain stiffness and large diameter triaxial testing, the interpretation of the data, and how this, together with back analysis exercises, was used to optimize the design of a 22m-deep cut and cover station box. The excavation has been completed and therefore this paper also presents the observed behavior.

Keywords: Small Strain Stiffness, Old Alluvium, Retaining Walls, Excavations Singapore, Field Performance

1 INTRODUCTION

The Singapore Old Alluvium (OA) is considered the oldest drift deposit in Singapore, consisting of mainly medium to very dense cemented clayey sand and fine gravels with lenses of silt and clay. It is highly variable (vertically and horizontally); making its geotechnical modelling challenging. Not surprisingly, site observations during the construction of underground spaces in Singapore showed that excavations in OA resulted in measured deflections that were significantly less than design predictions.

A section of the proposed Thomson East Coast Mass Rapid Transit (MRT) alignment (Figure 1), which run mostly through the OA, was part of the Land Transport Authority (LTA) plans for expansion of the Singapore rail system. Value engineering assessments carried out at during design development (around year 2014/2015) identified potential for design optimizations by investing in additional site investigations aiming to improve the characterization of OA geotechnical parameters.

The site investigations included laboratory and in-situ measurements of small strain stiffness and large diameter consolidated undrained (CU) triaxial testing. The interpretation of the data to review OA parameters conventionally used in Mohr Coulomb (MC) models were reported by M. Angeles et. al. (2016).

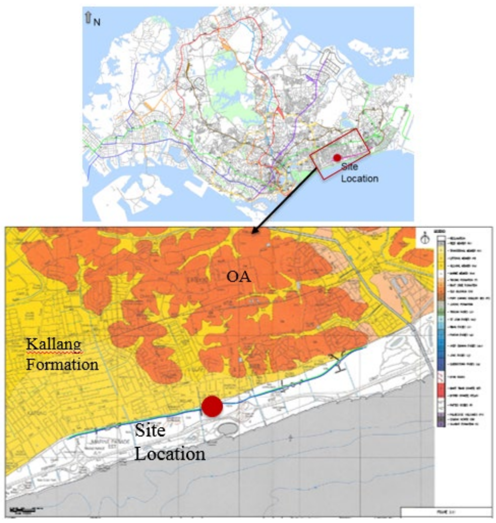


Figure 1 Site Location for Advanced Site Investigation.

This paper follows from the previous work by Angeles (2016) and presents the field performance of the same excavation, which was completed during 2018. The findings included in the previous publication are presented here to provide context for this work.

2 ADDITIONAL SITE INVESTIGATION

The site is underlain by a layer of reclamation fill with the OA present at an average depth of 5m below ground level (bgl) as shown in Figure 2.

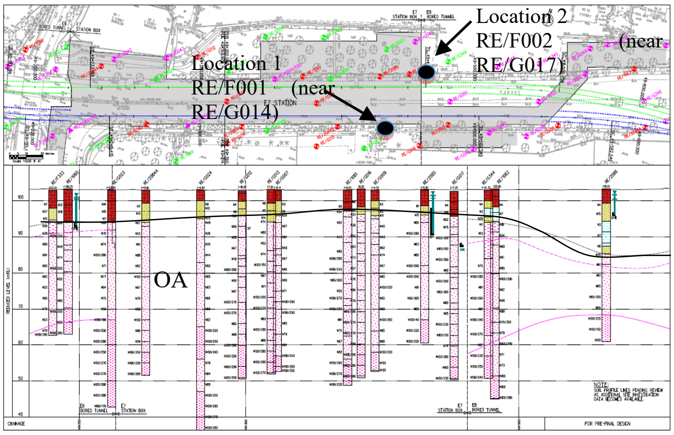


Figure 2 – Ground Conditions at the Site

2.1 Scope of Additional Site Investigations

The additional site investigations (SI) included:

- OYO Pressuremeter tests for estimation of drained Young's Modulus (E'). The tests were undertaken at various locations within the footprint shown in Figure 2.

- PS Logging to derive the in-situ Young's modulus at very small strains (Eo). The test was performed at two locations (RE-F001 and RE-F002).

- Consolidated Undrained Triaxials (CU) and Bender Elements to derive drained strength parameters (c' and ϕ') and laboratory Eo. The tests were carried out on 70mm diameter samples taken via continuous mazier sampling at boreholes RE-F001 and RE-F002.

3 OA PARAMETER INTERPRETATION

The OA parameters interpretation represent a 'characteristic' value in accordance to Eurocode 7 (EC7), which is defined as "a cautious estimate of the value affecting the occurrence of the limit state".

For an ideal elastic soil, the soil parameters cv, E', and k are related as shown in Equation 1. Based on the typical OA parameters of k=5x10^{-8} m/s (approximate higher range measured in rising head permeability tests) and E'=400MPa; it can be calculated that the steady state of groundwater flow could be achieved within a relatively short period of time (less than a month). Therefore, a drained behavior is considered appropriate in the context of cut and cover excavations.

$$cv = k.E'.(1-v)/(1+v)/(1-2v) \quad (1)$$

Where, cv: coefficient of vertical compressibility, E': drained Young's modulus, ν: Poisson ratio, k: permeability.

3.1 Drained Strength

The drained strength parameters are typically determined through a series of CU triaxial tests carried out on 38mm diameter samples. For the additional testing, the use of larger diameter samples (70mm) was proposed with the purpose of minimizing the effect of disturbances during sample preparation.

Figure 3a presents a combined plot showing results (s' vs t' plots) obtained with the 70mm diameter samples undertaken in OA(N>50) together with those obtained with the standard 38mm diameter tests. As observed, the results for the larger samples are consistently higher. This is likely to be a result, but not limited, to the following:

A larger sample provides a better representation of the intact in-situ condition.

No trimming is required as the 70mm diameter samples were tested directly on 70mm triaxial cells. See photo for an example of disturbance caused by a 70mm sample trimmed down to 50mm dia.

The proposed characteristic line c'=30, ϕ=35 is plotted in Figure 3a. This is consistent with the values proposed in earlier publications on CU/CD triaxial testing in OA(N>50) (W.W.Li, 2001).

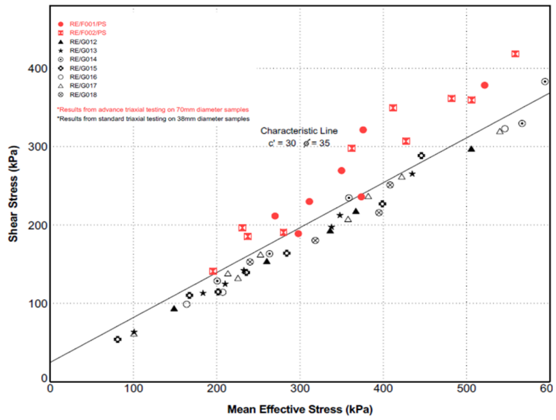


Figure 3a–OA CU Test Results in 70mm and 38mm samples

3.2 Drained Stiffness

The derivation of OA drained stiffness (E') is typically defined by interpretation of OYO pressuremeter tests (K.H. Goh, 2012). OYO testing is reliable for the large strain range whilst the accuracy of the equipment is reduced for the very small/small strain range. Therefore, to further justify stiffness parameters at the very small strain range PS logging and laboratory testing with bender elements was carried out.

3.2.1 OYO Pressuremeter

The variation of the OYO pressuremeter modulus over SPT 'N' against radial strain for the various classes of OA are shown on Figures 3b; where radial strain (cavity strain) equates to half the shear strain. Note that for interpretation, the OYO pressuremeter modulus is taken equivalent to a drained stiffness (E'). Shear strain levels observed for retaining walls typically vary between 0.01% and 0.1% (CIRIA C580, 1999). This equates to radial strains ranging from 0.005% to 0.05%. For this radial strain range, a characteristic value of E' = 4N (MPa) is selected in Figure 3b.

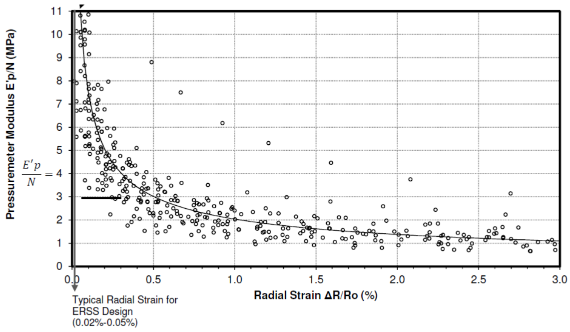


Figure 3b –OA OYO Pressuremeter

3.2.2 PS Logging and Bender Elements

The small strain stiffness (Eo) has been directly obtained from measurements of small strain shear modulus (Go) via in-situ PS logging and laboratory bender elements. The standard correlation Eo~3Go is assumed. The Eo values have been correlated to N value from the adjacent boreholes (RE/G014 and RE/G017). The correlation Eo /N with depth below OA level is presented in Figure 3c. A characteristic value of Eo = 12N (MPa) is proposed.

Leung et. al. (2010) have studied shear modulus degradation of Singapore OA (clayey and sandy) – Figure 3d. This shows that stiffness degrades to between 60% and 20% of Go. Given that Go and Eo are directly proportional it can be assumed that E' value for use in OA MC model should be representative of this range. For Eo = 12N, a stiffness ranging from 2.5N to 7.5N would apply for a typical retaining wall design. The proposed value of E' = 4N (MPa) is consistent with a characteristic value for these range.

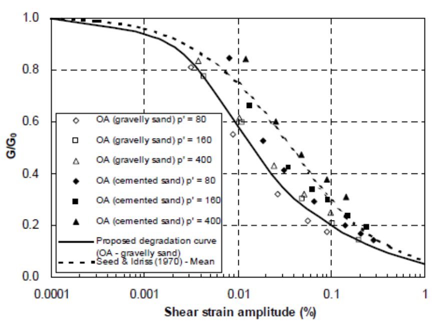
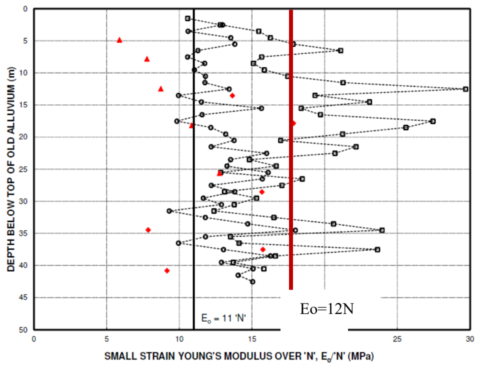


Figure 3d - Normalized Go of OA (after Leung et.al. 2010)



RE/F001 DEPTH BELOW TOP OF OLD ALLUVIUM (m)	'N'
2.5	100
5.5	79
8.5	100
11.5	71
14.5	82
17.5	59
20.5	68
23.5	100
26.5	100
29.5	84
32.5	73
35.5	89
38.5	100
40.5	100

RE/F002 DEPTH BELOW TOP OF OLD ALLUVIUM (m)	'N'
3.5	75
6	100
9	100
12	100
15	90
16.5	100
18.5	84
21.5	82
24.5	80
27.5	95
30.5	100
33.5	100
36.5	74
39.5	100
42.5	100

RE/F001 BENDER ELEMENT (LAB TEST)
RE/F001 PS LOGGING (IN-SITU TEST)
RE/F002 BENDER ELEMENT (LAB TEST)
RE/F002 PS LOGGING (IN-SITU TEST)
'N' = SPT BLOW COUNT

Figure 3c – OA In-situ/Laboratory - Small Strain Stiffness (Eo)

3.3 OA Proposed Mohr Coulomb (MC) Parameters

The proposed characteristic MC parameters for OA are presented in Table 2. Where O(E,D) N<30, O(C) 30<N<50, O(A,B) N>50.

STRATIFICATION		Unit	OLD ALLUVIUM: RESIDUAL SOIL	DESTRUCTED	DISTINCTLY WEATHERED	PARTIALLY WEATHERED	UNWEATHERED
GEOLOGICAL CLASSIFICATION			O(E)	O(D)	O(C)	O(B)	O(A)
Unit Weight	γ	kN/m³	20				
Effective Angle of Friction	ϕ'	Deg	30		33	35	
Effective Cohesion	c'	kPa	0		10	30	
Undrained Shear Strength	c_u	kPa	4 'N' (1)				400
At Rest Earth Pressure Coefficient	K_0	-	0.7	0.7	0.7	0.7	0.7
Young's Modulus	E_u	MPa					
	E'	MPa	4 'N' (1)				400
Permeability	K_{des}	m/s	$5x10^{-8}$				

Table 2 – OA Parameters for ERSS Design

4 VALIDATION WITH BACK ANALYSIS

A back-analysis exercise using the parameters proposed in Table 2 was carried for a 23m deep excavation built using an embedded retaining wall system (ERSS) in Singapore OA. The exercise resulted in improved predictions (refer to M. Angeles, 2016) and provided confidence on the interpretation of the MC parameters. The detailed design was carried out based on the parameters presented in Table 2.

5 MRT STATION DESIGN OPTIMISATION

With the use of improved OA parameters, the embedded retaining wall system (ERSS) design for a future MRT Station was optimized.

D-Wall thicknesses were optimized to 1.0m and 0.8m from 1.2m to 1.0m for most of the station excavation. In addition to D-Wall thicknesses, a construction sequence optimization was achieved by eliminating the bottom strut S2 – Section B in Figure 7 shows no struts from concourse to final excavation level. Eliminating one layer of steel struts equated to savings of up to 2.5M SGD, in addition to programme savings. The investment in the additional site investigations was about 150,000 SGD.

6 SITE PERFORMANCE

To review the performance of this deep excavation the ERSS deflection was comprehensively monitored via the installation of inclinometers. Refer for example to Section B in Figures 6 and 7.

Based on the field observations, the deflection of diaphragm wall (D-Wall) was reviewed in comparison to design predictions. By adopting the proposed OA parameters, the measured maximum lateral wall deflection followed the actual performance more closely than what would have been predicted with the previous conventionally used OA parameters (e.g. E’ = 2N).The wall deflection was still slightly over-predicted by a factor of 1.5 to 2.0, being larger during the cantilever stage. This could be expected as the selected characteristic parameters are meant to represent a cautious estimate of value in accordance with Eurocode 7.

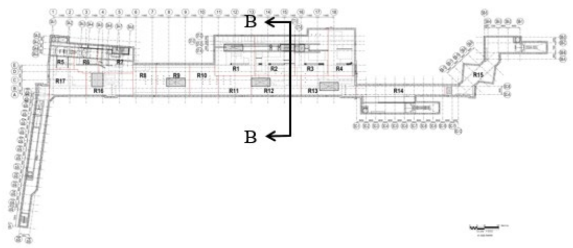
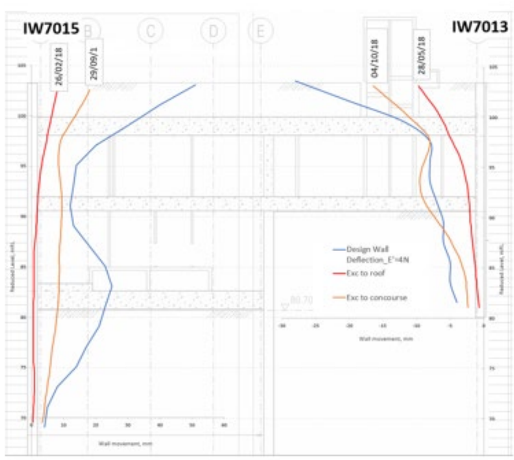


Figure 6 Field Performance Monitoring Section



SECTION B-B

Figure 7 Comparison of Actual vs Predicted Deflections

7 CONCLUSIONS

Additional site investigations were carried out at a future MRT site underlain by OA with the intention to optimize conventionally used MC parameters. The interpretation considered the small strain stiffness (Go) from PS logging and laboratory bender elements, OYO pressuremeter tests, and OA stiffness degradation curves. The proposed value E’=4N is about double the value typically used in the industry.

CU triaxial testing was carried out using larger 70mm diameter samples. This resulted in higher strength parameters as compared to those obtained with the commonly used 38mm dia.

The use of the improved set of MC parameters allowed for design optimizations of a 22m deep excavation, which was constructed with thinner D-Walls and without intermediate strutting from concourse to final excavation level.

Site measurements resulting from this excavation together with the results of the additional testing have provided valuable information to improve the geotechnical modelling of excavations in OA. The MC model may still over-predict displacements. However, for design purposes this is considered appropriate as the selected characteristic parameters are meant to represent a cautious estimate.

Further optimizations may be achieved in future via the use of the Observational Method as described in EC7 and CIRIA 760. This would require the definition of “most probable” parameters (justified by back-analysis) instead of “characteristic” values. In this case, omission of struts would depend on the actual performance during construction with an option to introduce additional support should actual deflection exceeds design predictions.

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