Ground Conditions and Geotechnical Parameters for the Perth Waterfront Development, Perth CBD

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ABSTRACT

The $2.6B Perth Waterfront Project is being undertaken by the WA State Government in partnership with the private sector to reconnect the Swan River with the Perth Central Business District. The project will involve the re-development of approximately 10 hectares of land on the Swan River Foreshore and will feature a 2.7 hectare inlet surrounded by landscaped terraces, boardwalks and promenades. Development sites surrounding the inlet will be sold to private developers for the construction of office, retail and apartment buildings of up to 36 levels. Major earthworks are scheduled to start in 2012. Geotechnical investigations for Phases 1 to 3 of the project were undertaken between 2007 and 2011. This paper provides an introduction to the project, an outline of the geology underlying the project area and summarises the geotechnical design parameters adopted for the various geological units encountered.

Keywords: Perth, waterfront, Guildford Formation, Swan River Alluvium, geotechnical, geology.

1 INTRODUCTION

The $2.6B Perth Waterfront Project is being undertaken by the WA State Government (providing $440M for public works) in partnership with the private sector to reconnect the Swan River with the Perth Central Business District. The project will involve the re-development of approximately 10 hectares of land on the Swan River Foreshore and will feature a 2.7 hectare inlet surrounded by boardwalks and promenades. Development sites surrounding the inlet will be sold to private developers for the construction of office, retail and apartment buildings of up to 36 levels.

The project will be developed on land previously reclaimed from the Swan River and is to be located between William Street, Barrack Street, The Esplanade and the Swan River. Road modification and realignment will extend towards the Kwinana Freeway interchange and along Riverside Drive to the Narrows Bridge. The overall project area and artist's impression are illustrated in Figure 1.

Major earthworks and construction are scheduled to begin in 2012 with all public works due for completion by mid 2015.

Figure 1. (a) Project Location (air photo © 2012 DigitalGlobe) and (b) artist impression (© 2012 MRA)

2 GEOLOGICAL SETTING

2.1 Geological History

During the early Tertiary Period (65 million to 2.6 million years ago) rising relative sea levels resulted in the deposition of sediments that formed the Kings Park Formation. The sediments were deposited in a shallow marine to estuarine environment and infilled a deep river valley incised through the underlying Cretaceous and Jurassic aged materials. The infilled valley broadly coincided with the current position of the Swan River. The Kings Park Formation forms the bedrock underlying the Perth CBD.

Subsequent changes in relative levels between land and ocean exposed the Kings Park Formation as a land surface during the late Tertiary Period. There was a break in further sedimentation until the start of the deposition of alluvium during the Quaternary Period (2.6 million years ago until the present). These younger alluvial soils are complex in nature and may be described as interbedded sands, silts and clays. They were deposited mainly as a result of the alluvial action of the river system but also include at least one marine incursion. These alluvial soils have historically been referred to as the Guildford Formation[1].

The Quaternary Period has been characterised by periodic sea level fluctuations. Episodes of erosion by rivers during glacial periods have resulted in the formation of deep buried channels (paleochannels). Gordon (2003) identified two such paleochannels passing through the Perth Waterfront project site that cut into the Kings Park Formation.

The older of the two paleochannels, denoted Channel 6, was attributed by Gordon (2003) to the penultimate glacial period that occurred approximately 130,000 to 190,000 years ago. The channel is overlain and infilled with Guildford Formation soils. The younger paleochannel, denoted Channel 2, is believed to have been incised during the latter part of the last glacial period, approximately 10,000 to 25,000 years ago. This channel is infilled by soft estuarine and marine muds that form the most recent natural deposit and are currently still being deposited within the waters of the Swan River. Collectively these clays are referred to as Swan River Alluvium (SRA)[1].

2.2 Recent Reclamation

Over the last 150 years, a substantial part of the Perth Foreshore has been reclaimed from the Swan River. Reclamation works began in the late 1800s with the infilling of the shallow marshy waters between the William Street and Barrack Street jetties. The reclaimed land extended approximately 100 m south of the original shoreline and eventually extended east to the Causeway.

In 1954 additional reclamation works began as part of the earthworks for construction of Narrows Bridge. This involved the reclamation of land (29 ha) located to the west of the project site. The reclamation work was mostly complete by early 1958. A second stage of reclamation (8 ha) took place over the period of 1950 to 1970 in order to accommodate the Narrows Interchange.

3 SITE INVESTIGATION AND LABORATORY TESTING

The Phase 1 geotechnical investigation for the project commenced in 2007. An additional two investigation phases were since carried out with the final Phase 3 investigation completed in 2011.

Field investigations included the excavation of test pits, the drilling of boreholes, CPT testing and dilatometer testing at both on-land locations and over-water (nearshore) locations within the Swan River. SPT testing was conducted in the boreholes and U63 tube samples obtained of clayey soils. The completed testing provided geological information for about 200 locations around the project site.

[1] More recently there has been a proposal to sub-divide and rename the Guildford Formation soils underlying the CBD to the Perth Formation and the Swan River Formation (Gozzard, 2007). For the purposes of this paper, the terms 'Guildford Formation' and 'Swan River Alluvium' have been retained.

Laboratory testing included index tests on disturbed samples and oedometer tests and triaxial tests on undisturbed samples. Point load index tests, UCS tests and shear wave velocity tests were carried out on rock samples.

4 GEOLOGICAL MODEL

Based on the geological history of the site, a geological model was established that consisted of four units. The geological units are discussed below (from youngest to oldest).

4.1 Fill Material

Fill material was deposited as part of the previous reclamation works and covers the on-land portion of the site. The fill material predominantly comprises clean quartz sand but also includes minor shell and soft clay layers. To the east of William Street, the fill thickness is fairly consistent at about 1.5 m to 2.0 m. To the west of William Street, the thickness of fill increases up to about 20 m towards Narrows Bridge. The fill is generally in a medium dense to dense state.

4.2 Swan River Alluvium

The SRA typically comprises dark grey to black high plasticity silty clay, although some sandy clay and clayey sand lenses were also encountered. The clay is typically very soft to firm with an organic content of between 1% and 12%. A very loose shell-rich sandy layer was encountered underlying the clayey SRA in some of the over-water boreholes. The greatest thickness of SRA is associated with a paleochannel (Channel 2) where up to 23 m thickness of the unit was encountered. East of William Street the thickness of SRA is generally less than one metre.

4.3 Guildford Formation

The Guildford Formation is a complex sequence of interbedded sand, silt and clay. Clay layers within the Guildford Formation are typically high plasticity. The Guildford Formation is overconsolidated and as such the clays typically have a stiff to very stiff consistency. Sand layers are predominantly quartz and are generally medium dense to dense.

4.4 Kings Park Formation

The Kings Park Formation (KPF) forms the bedrock underlying the entire development site and comprises a dark grey siltstone containing trace shell fragments. The strength of the KPF was highly variable but typically ranged between low to medium strength. Drill core shows a relative absence of jointing. The surface elevation of the KPF ranges between RL -17 m AHD and RL -35 m AHD with the deeper areas corresponding to the two paleochannels.

5 THREE DIMENSIONAL GEOLOGICAL MODEL

The geological data collected for the project was combined with data from previous investigations conducted in the vicinity of the project site. In all, approximately 900 test locations were identified, assessed and used to construct a 3D geological model for the site. The 3D model was developed using Environmental Visualisation Systems (EVS) software developed by C Tech Development Corporation.

A sample output from the model is shown in Figure 2. Besides its aesthetic appeal, the model had practical applications, such as assisting with project planning to ensure that critical project infrastructure was not located in areas underlain by extensive deposits of SRA.

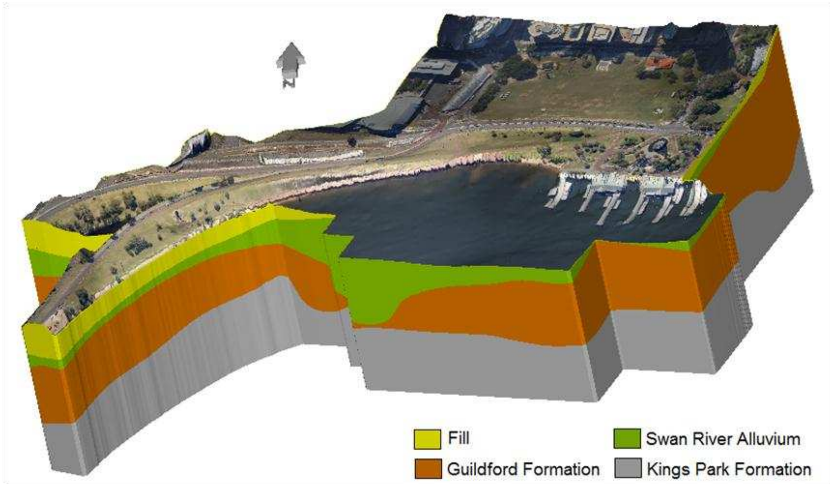

Figure 2. Three dimensional geological model developed for the project

6 PALEOCHANNELS

The field testing and 3D modelling confirmed the position of two paleochannels of the Swan River within the project site. Due to the similarity of the paleochannel alignments, it is inferred that these are the Channel 2 and Channel 6 paleochannels described in Gordon (2003).

Channel 6, the older of the two paleochannels, is infilled by Guildford Formation soils and can be traced from the north east corner of the project area to beyond the southern end of William Street. The alignment of the paleochannel can be seen in the surface generated for the base of the Guildford Formation (Figure 3a). The paleochannel is about 20 m to 25 m deep with a base at about RL -32 m AHD to RL -34 m AHD.

The more recent paleochannel, Channel 2, is infilled with SRA and cuts across the project area in an approximately northerly to north-westerly direction, south west of the intersection of William Street and Riverside Drive. The paleochannel alignment is observed in the surface generated for the base of the Swan River Alluvium (Figure 3b). The paleochannel is about 15 m to 20 m deep with a base at about RL -25 m AHD.

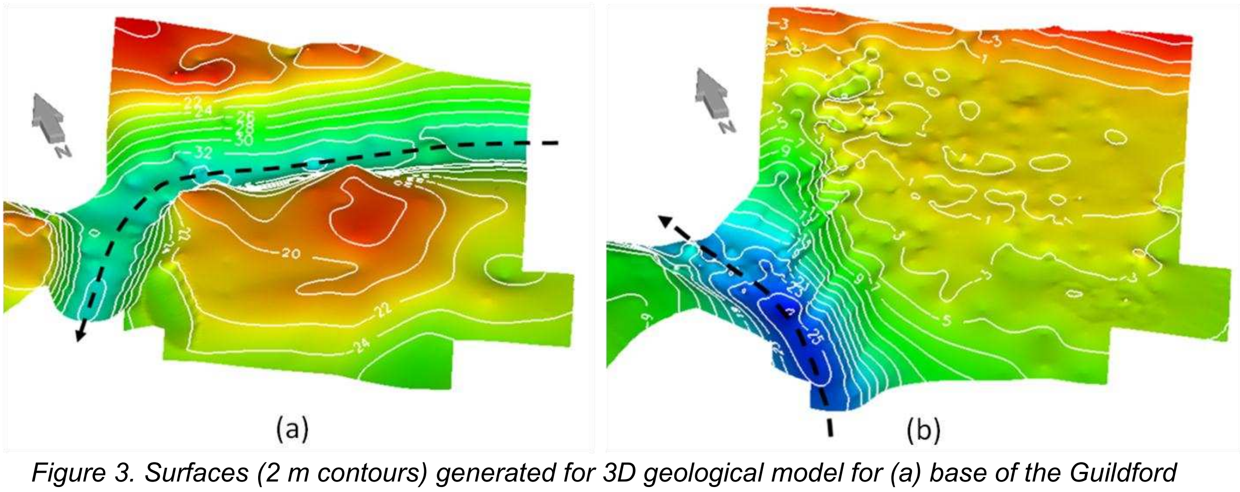

Figure 3. Surfaces (2 m contours) generated for 3D geological model for (a) base of the Guildford Formation and (b) base of SRA. Inferred paleochannel alignment indicated by dashed arrow

7 GEOTECHNICAL PARAMETER ANALYSIS

The extensive scope of this project has enabled the collation of a significant set of data related to the consolidation and shear strength parameters for the SRA and the Guildford Formation. This set of data has been augmented by data collected from other major projects located in the vicinity of the site

7.1 Shear Strength Parameters

The results of consolidated single stage and multi-stage isotropically undrained (CIU) triaxial tests on undisturbed SRA and Guildford Formation samples are presented in Figure 4 in the form of a stress path plot where the point of maximum stress obliquity (i.e. maximum ratio of (σ'_1/σ'_3)) is plotted. In the case of multi-stage tests, only the results from the first stage have been considered because the first test stage may establish a plain of weakness that could affect the shear strength measured during subsequent stage of the test. From Figure 4, the best fit effective friction angle for the SRA and Guildford Formation is 31° and 37° respectively. The test data is surprisingly consistent giving a high degree of confidence in the results. For design purposes, a more conservative value than that derived from the best fit line would be used.

The s_u/p'_o ratio has also been evaluated from the results of the CIU triaxial test data where s_u is the undrained shear strength associated with the point of maximum stress obliquity from the test and p'_o is the sample pre-shear effective stress. Analysis of the data showed no strong correlation between either initial moisture content, sample elevation or sample depth. Hence the s_u/p'_o ratio has been treated as a random variable with summary statistics and the confidence interval for the mean as presented in Table 1. Thus in spite of the fact that the effective shear strength parameters are well defined for both the SRA and the Guildford Formation (Figure 4), the undrained shear strength cannot be readily predicted based on the data collected during this investigation.

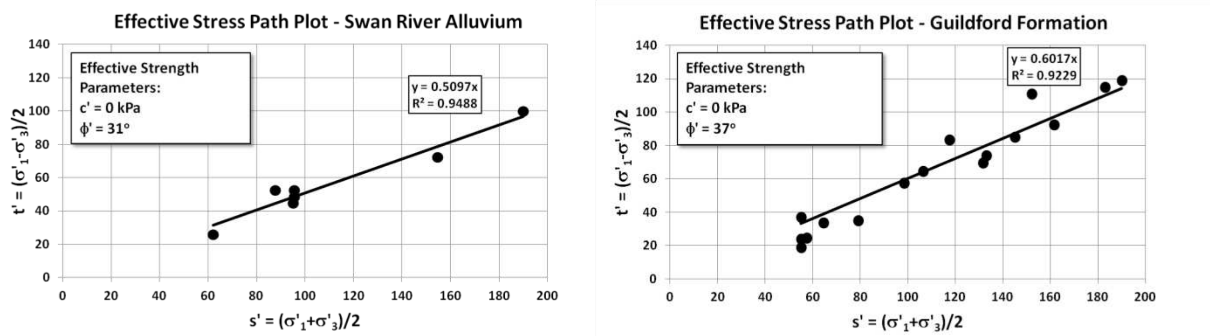

Figure 4. Effective stress path plot for Swan River Alluvium and Guildford Formation

Table 1: s_u/p'_o Ratio from Triaxial Testing

Unit	n	Min.	Max.	Average	Median	SD	COV	95 % Confidence Interval of the Mean	
								Upper	Lower
Swan River Alluvium	7	0.14	0.56	0.33	0.30	0.13	39%	0.45	0.21
Guildford Formation	13	0.30	1.2	0.60	0.60	0.30	39%	0.80	0.50

Notes: n is the number of data points; SD is the standard deviation; COV is the coefficient of variation

The undrained shear strength from dilatometer tests, vane shear tests (Coffey, 2004) and unconsolidated undrained triaxial tests are shown on Figure 5a for the SRA and Figure 5b for the Guildford Formation. Also shown on this figure is the predicted undrained shear strength from the s_u/p'_o ratios presented in Table 1 (95% confidence intervals). From Figure 5a and 5b, the predicted strengths bracket the data quite well except for the UU triaxial data that generally estimates greater strengths compared to the other test data.

The undrained shear strength determined from CPT testing for a CPT location within the paleochannel area (Channel 2) is presented in Figure 5c together with the results of vane shear tests from Coffey (2004). The undrained shear strength back calculated from the lower confidence interval s_u/p'_o ratio agrees well with the CPT data for a N_{kt} value of 17 below an elevation of about RL -20 m AHD. At higher elevations, the predicted undrained shear strength from the CPT data falls between the undrained shear strength from the predicted upper and lower confidence interval s_u/p_o' ratios. A particular feature of the CPT undrained shear strength is that it does not predict a consistent increase with depth and in fact predicts a decrease in strength with depth between RL -14 m AHD and RL -22 m AHD.

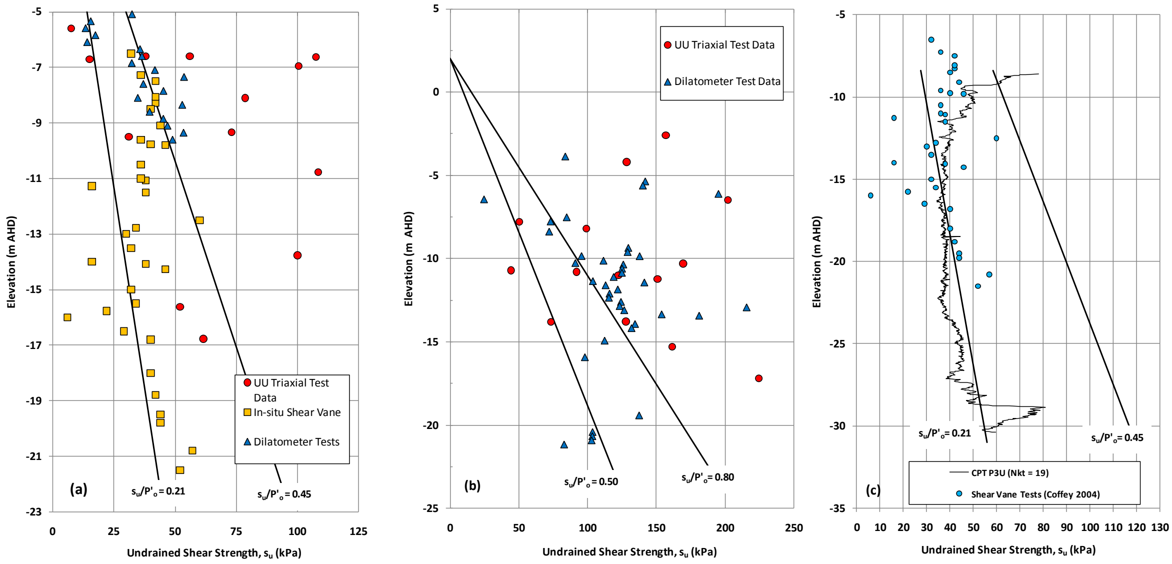

Figure 5. Undrained Shear Strength Profiles for (a) SRA (b) and Guildford Formation. (c) SRA infill of paleochannel.

7.2 Consolidation Parameters

Summary statistics and confidence intervals for the mean consolidation parameters for the SRA and the Guildford Formation are shown in Table 2 and Table 3 respectively. Inspection of the data does not indicate correlations between initial moisture content, sample elevation or sample depth.

Table 2: Summary Statistics: Consolidation Parameters for the SRA

Parameter	n	Minimum	Maximum	Average	Median	95% Upper and Lower Confidence Interval of the Mean	
						Upper	Lower
e_o	18	1.01	3.21	2.04	1.99	2.27	1.81
w_o (%)		36.7	124.9	75.3	72.2	84.5	66.1
ρ_d (t/m^3)		0.63	1.25	0.86	0.86	0.93	0.80
ρ_w (t/m^3)		1.33	1.71	1.49	1.48	1.54	1.45
OCR		0.4	3.2	1.3	1.0	1.7	0.9
C_c		0.296	1.760	0.922	0.981	1.090	0.754
C_r		0.003	0.133	0.072	0.077	0.090	0.054
$C_c/(1+e_o)$		0.099	0.051	0.304	0.306	0.358	0.251
$C_r/(1+e_o)$		0.001	0.051	0.024	0.026	0.031	0.018

Notes: e_o is the initial void ratio, w_o is the initial moisture content, ρ_d is the initial dry density, ρ_w is the wet density, OCR is the overconsolidation ratio, C_c is the compression index and C_r is the recompression index.

Table 3: Summary Statistics: Consolidation Parameters for the Guildford Formation

Parameter	n	Minimum	Maximum	Average	Median	95% Upper and Lower Confidence Interval of the Mean	
						Upper	Lower
e_o	21	0.496	1.59	0.937	0.841	1.070	0.805
w_o (%)		15.9	49.8	32.6	32.2	37.0	28.2
ρ_d (t/m^3)		1.02	1.77	1.40	1.44	1.49	1.30
ρ_w (t/m^3)		1.46	2.05	1.84	1.87	1.91	1.77
OCR		0.4	9.5	3.3	3.2	4.5	2.2
C_c		0.061	0.500	0.222	0.216	0.274	0.169
C_r		0.003	0.177	0.027	0.020	0.043	0.010
$C_c/(1+e_o)$		0.036	0.215	0.110	0.110	0.130	0.090
$C_r/(1+e_o)$		0.002	0.096	0.014	0.009	0.023	0.005

Notes: e_o is the initial void ratio, w_o is the initial moisture content, ρ_d is the initial dry density, ρ_w is the wet density, OCR is the overconsolidation ratio, C_c is the compression index and C_r is the recompression index.

Measured coefficient of consolidation (C_v) values from oedometer testing ranged between 1 m^2/year and 140 m^2/year for SRA and between 1 m^2/year and 300 m^2/year for the Guildford Formation. For design purposes, a lower bound C_v value of 3 m^2/year was recommended for SRA and an average C_v value of 100 m^2/year was recommended for the Guildford Formation (for unloading and reloading stress paths at less than the pre-consolidation stress).

8 CONCLUSION

The geological history of the Perth Waterfront development site indicates that the geology of the site is complex with two paleochannels including one approximately 20 m deep in-filled with soft to firm high plasticity clays called the Swan River Alluvium (SRA). An extensive database exists for the site that includes around 900 on-land and over-water test locations. This extensive database has enabled a three dimensional database to be established for the site that has been useful as an aid to locating important infrastructure for the site in order to reduce development costs.

The effective shear strength parameters for the SRA and the Guildford Formation are well defined but a full understanding of the undrained shear strength of the SRA at the project site remains elusive.

9 ACKNOWLEDGEMENTS

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