The paper was published in the proceedings of the 11th International Symposium on Field Monitoring in Geomechanics and was edited by Dr. Andrew M. Ridley. The symposium was held in London, United Kingdom, 4-7 September 2022.

11TH INTERNATIONAL SYMPOSIUM FIELD MONITORING IN GEOMECHANICS

A Case History on Observational Method for Deep Excavation in Singapore

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Abstract

The Observational Method (OM) frameworks for deep excavation works in Singapore was launched in September 2019 by the Building and Construction Authority (BCA). The OM frameworks required both designs using normal and OM approach submitted to BCA for approval prior the construction works. The implementation of the OM will be decided based on the instrumentation monitoring results during construction. This paper outlines the OM frameworks and presents a case history for a deep excavation project that has been successfully carried out using the OM approach.

The case history involved a project with basement excavation of 8.5m depth generally and localized 11.5m depth at pit area in thick soft recent deposits of more than 30m in depth. The retaining system consists secant bored piles (SBP) wall supported with struts. The base design following the code requirements using the characteristic soil parameters required 3-level struts to support the excavation. In the OM design using the average (most probable) soil parameters, omission of 3rd level struts to 2-level struts was achieved. Extensive instrumentation for monitoring of the retaining wall, struts and surrounding structures had been carried out during the excavation. Based on the monitoring results, the 3rd level struts were judiciously omitted following the OM design. The implementation of the OM for the project resulted in substantial time and cost saving.

Keywords: Observation Method Framework, Excavation, Instrumentation and Monitoring, Time/Cost Saving

1. Introduction

The basement construction for a high-rise building development involved an excavation depth of about 8.5m depth at general area and 11.5m depth locally at lift pit area. The site of the development is located on reclaimed land with thick recent soft clay deposits of the Kallang Formation of Singapore. Due to the poor ground conditions with the maximum depth of the Kallang Formation layers varying from 35m to 45m, rigid retaining wall extending to hard strata below the Kallang Formation had been adopted for the basement excavation works. The retaining wall will be functioning both as earth retaining structure as well as part of the foundation system supporting the tower block. Besides the rigid retaining wall, the foundation system consists bored piles installed within the basement and these foundations are connected by a single pile cap forming a raft at the entire basement of the tower block.

Despite the rigid retaining wall extending well below the Kallang Formation, 3-level struts supporting the 8.5m excavation with an additional strut locally at the pit area are required based on the conventional design using the characteristic design parameters. As the 3rd level struts are located within the pile cap, the casting of the pile cap is required to be divided in two parts – cast lower part of pile cap and remove 3rd level struts before complete casting of the pile cap.

The 2-stage casting of the pile cap would be tedious process to ensure continuity of the rebars and time consuming due to the obstruction of the 3rd level struts. As such, the plausibility of the omission of the 3rd level strutting was explored using the OM design approach based on the most probable design parameters following the guideline stipulated in the BCA's OM framework (BCA 2019).

2. Outline of OM Framework

The Observational Method (OM) framework was launched by the Building and Construction Authority (BCA) to promote work efficiency and construction productivity without compromising safety. The guideline for the adoption of OM in earth retaining or stabilising structures (ERSS) allows project parties to adopt optimised design during construction if better performance is realised. Based on guideline on the applicability of OM stipulated in Table 1, the proposed ERSS system is applicable to implement the OM design.
In the OM framework, authority approval of the design plans shall be obtained before the commencement of the construction works. The design incorporating relevant considerations for the Characteristic Scenario (CS)

and an additional Probable Scenario (PS) shall be carried out based on 'characteristic' and 'most probable' design parameters, respectively. In the OM design, various OM levels for the CS & PS and the decision stage (on when to adopt the appropriate design scenario) during construction are developed. The design considerations and required actions during construction are summarized in Table 2. Example of various OM levels are shown in Figure 1. The administration of the OM would depend on the actual ERSS performance at the site via site instrumentation results and observations.

Applicability of Proposed ERSS System for Adopting OM

The applicability for adoption of OM	The ERSS scheme is multi-prop and do not fall under the following category:
	- Floting ERSS (where wall toe is not embedded into stiff soil with SPT N>15) that are within Zone 1 or Zone 2 as defined in BCA's Advisory Note 1/09 for ERSS
	- Slope - earth slopes, open-cut slope and nailed slopes
	- Cantilever / Single strut ERSS
	- Mined excavation
Pre-consutation with BCA	QPs pre-consult BCA to confirm the applicability of the OM proposal

Instrumentation and Monitoring Requirements

Instrumentation interval	Array @ maximum 30m interval
Instrumentation per array	Inclinometer, support strain gauge or load cell
Instrumentation frequency	After Decision Stage of adopting PS till casting of base slab or any subsequent critical construction stage: Inclinometer: Daily Support strain gauge or load cell - at least daily. QP to review and decide the need for real time monitoring with SMS

Table 1: Applicability of Proposed ERSS System for Adopting OM and Instrumentation Requirement

OM Design using Characteristic and Most Probable

Key aspects	Criteria
Stability checks (e.g. wall toe embedment, global stability)	Based on 'characteristic' parameters
Analysis for retaining wall(s) and support(s)	Minimally 2 set of runs: • Run-1 based on 'characteristic' parameters corresponding to the Characteristic Scenario (**CS**) • Run-2 based on 'most probable' parameters corresponding to the Probable Scenario (**PS**)
Design of retaining wall & support(s)	Based on the most onerous analysis of **CS** and **PS** (i.e. envelope of Run-1 and Run-2)
Compatibility between **CS** and **PS**	The adopted systems shall be compatible all the way such that the switch back to CS from PS can be made at any time during the construction process without creating structural issues or obstructions that makes the reversion impossible.
Design adopted at the **start** of construction for retaining wall and support(s)	Based on **CS**
Potential optimisation during construction phase	Applicable to the reduction of struts/props only when the actual performance of the ERSS at the **Decision Stage** and subsequent stages of construction are within the design limits of the **PS**
Ground water	Onerous ground water condition is to be adopted.

Actions to be Taken at OM Levels During Construction

#	Terminology	Performance of ERSS at the stage of construction considered	Action
1	OM implementation Zone	Within OM Implementation Level	Performance via PS is well on route. QP may proceed with the next stage of excavation via PS#
2	Decision Zone	Between OM Implementation Level and OM Design Level	Performance via PS is marginally on route QP to deliberate the adoption of CS or PS
3	Characteristic Design Zone	Exceeded OM Design level but still within PDL	OM cannot be materialised. Current scenario – CS QP to proceed with the next stage of excavation via CS Current scenario – PS QP to immediately instruct the erection of supports# and reversion* of the proposal to CS
4	Remedy Measure Zone^	Breached PDL (still within WSL)	QP to review the design, assess the need for strengthening and subsequently make amendment submission before proceeding with further excavation QP to report to BCA via email
5	Alert Level^ (AL)	Breached Alert Level	QP to closely monitor the performance of the ERSS
6	Work Suspension Level^ (WSL)	Breached Work Suspension Level	QP to immediately suspend all excavation work, report to BCA and carry out strengthening works

- to specify in the approved plans that the material of supports based on CS design (not erected when adopting the PS design) are to be kept on site/store that can readily be deployed within a day; from the Decision Stage till casting of base slab or any subsequent critical stage.
* - compatibility between **CS** and **PS**
^ - as per standard practises independent of OM

Table 2: OM Design Guideline

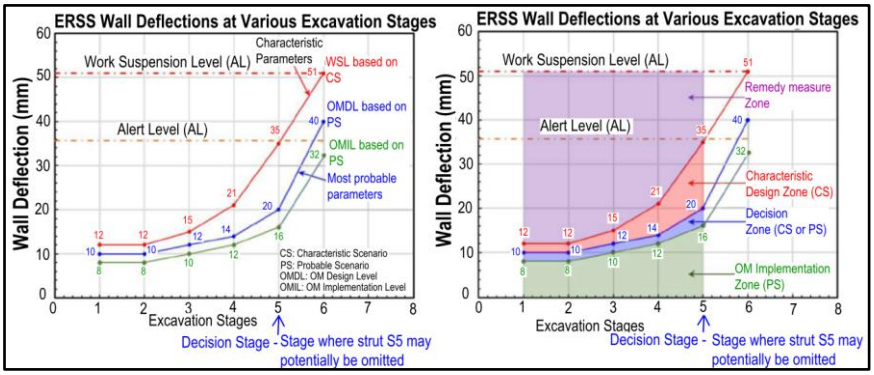

Figure 1: OM Zones and Review Levels

3. Outline of Excavation Works

The conventional bottom up excavation method was planned to be carried out for the basement construction with the retaining wall supported by multi-layers of temporary steel struts. The Characteristic Scenario (CS) was designed to be supported with 3-level struts at the general basement area. The OM design for the Probable

Scenario (PS) was designed to be supported with 2-level struts. Figure 2 shows plan and section views of the proposed retaining system (retaining walls supported with struts). The construction sequences are summarized in Figure 3 for both CS and PS. The OM decision stage would be at the stage where the excavation reaches to the level below the planned 3rd level struts in the CS. The omission of the 3rd level struts would be dependent on the monitoring results of the wall deflection whereby the 3rd level struts could be omitted if the wall deflections are measured to be less than OM design level (OMDL). The 3rd level struts would be required if OM design level (OMDL) is exceeded.

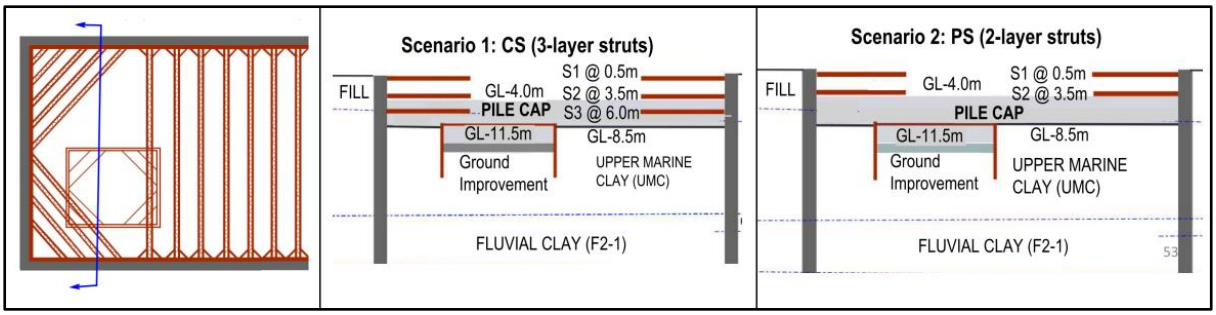

Figure 2: Plan and Section Views of Proposed Retaining System

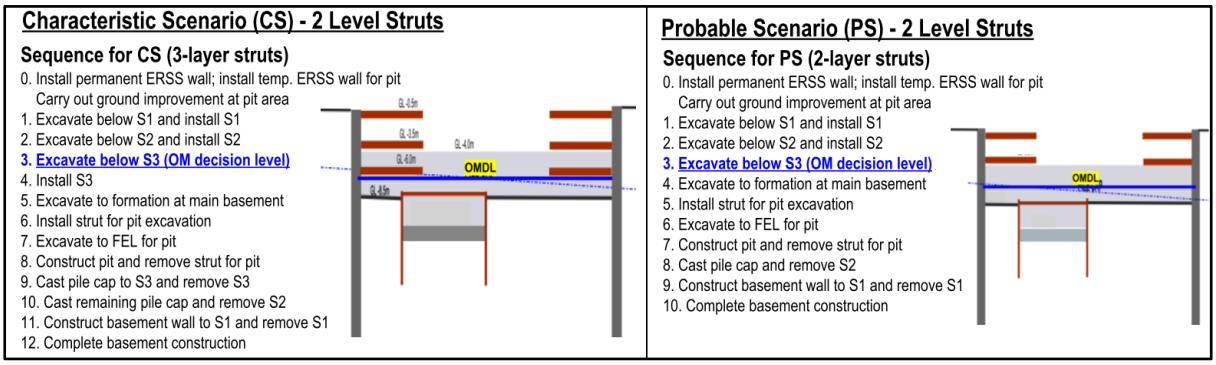

Figure 3: Sequence of Construction for CS and PS

4. Derivation of Geotechnical Design Parameters

The ground at the site consists thick soft recent deposits of Kallang Formation of Singapore including (a) 2 layers of soft Marine Clay, MC (main recent deposits at the site); (b) medium stiff Estuarine Clay (E) locally found between the marine clay layers and below the Lower Marine Clay; (c) loose to medium dense Fluvial Sand (F1); and (d) medium to stiff Fluvial Clay The main geotechnical design parameters for the design of the Earth Retaining and Stabilising Structure (ERSS) are (i) shear strength parameters and (ii) modulus of elasticity. As the ground at the site consists thick layers of soft clay, the design of the ERSS would be governed by the undrained shear strength parameters of the soft clay layers. Therefore, the site investigation works had been planned with extensive field tests (vane shear tests) and laboratory tests (index properties tests, unconsolidated-undrained, UU triaxial compression tests and consolidation tests on undisturbed samples) to obtain the shear strength and stiffness parameters of the Kallang Formation Clay layers.

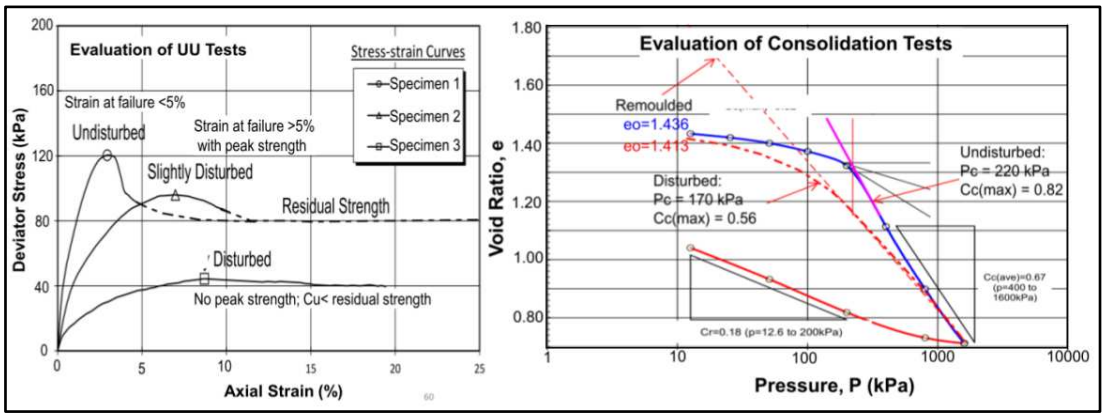

Figure 4: Evaluation of UU and Consolidation Tests Results

Detailed assessments of the test data have been carried out to obtain the representative design parameters for optimization of the design. From the evaluation of the test data, samples or specimens that are deemed to be disturbed or unrepresentative were removed in determining the design parameters. Evaluations of sample disturbance for UU and consolidation tests are illustrated in Figure 4.

Undrained Shear Strength (Cu): Field vane shear tests in soft clay layers and laboratory UU tests on undisturbed soil samples were carried out to determine the undrained shear strengths of the Kallang Formation clay layers. Based on average plasticity index (Ip) of 35 to 40 for the marine clay layer, correction factor of 0.85 to 0.9 using Bjerrum's recommendation would be required to obtain Cu from vane shear strength. However, from the plot of Cu (UU test) versus Su (VST), a correlation factor of 1.0 between Cu and Su is applicable for the marine clay at the site: Cu = 1.0*Su (VST) (Figure 5).

The Cu values of the marine clay can also be estimated from pre-consolidation pressure (Pc') obtain from the consolidation tests. The following correlations between Cu and Pc' (Figure 6) were derived based on the plot of Cu versus Pc': Cu = 0.27*Pc' for Pc' ≤ 200 kPa and

Cu = 54 + 0.15*(Pc'-200) kPa for Pc' > 200 kPa

From the results of VST and UU tests, Cu of the Kallang Formation clay layers are plotted in Figure 7. The Characteristic and Most Probable Cu values are derived and summarized in Table 4.

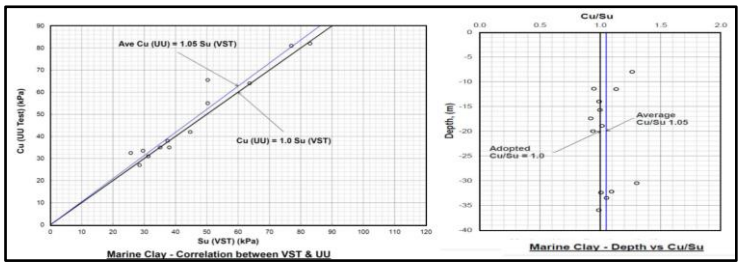

Figure 5: Correlation between Cu (from UU Tests) and Su (from Vane Shear Tests, VST)

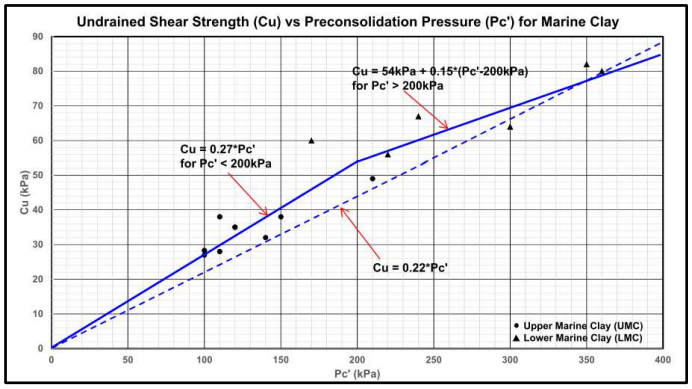

Figure 6: Correlation between Cu and Pc' for Marine Clay

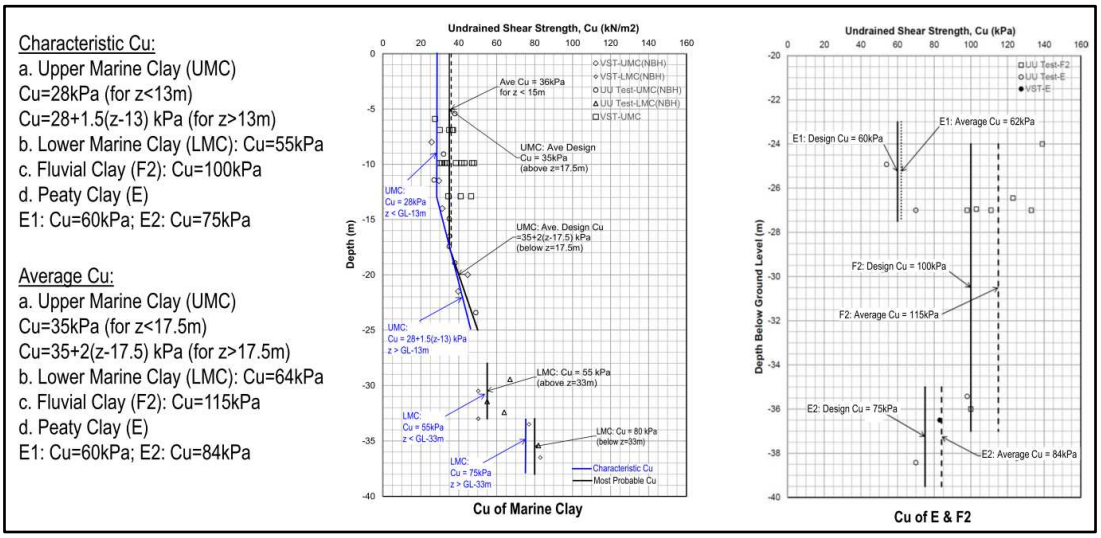

Figure 7: Undrained Shear Strength (Cu) of Kallang Formation Clay

Consolidation Properties: Figure 8 presents the unit weight (γ), initial void ratio (e_o), compression index (c_c and c_r) and pre-consolidation pressure (Pc') for the Kallang Formation clay layers. The consolidation properties of the marine clay layers are plotted in Figure 8. The results of the consolidation tests showed that the marine clay layers are normally to slightly over-consolidated with over-consolidation ratios (OCR) varying from 0.9 to 1.2.

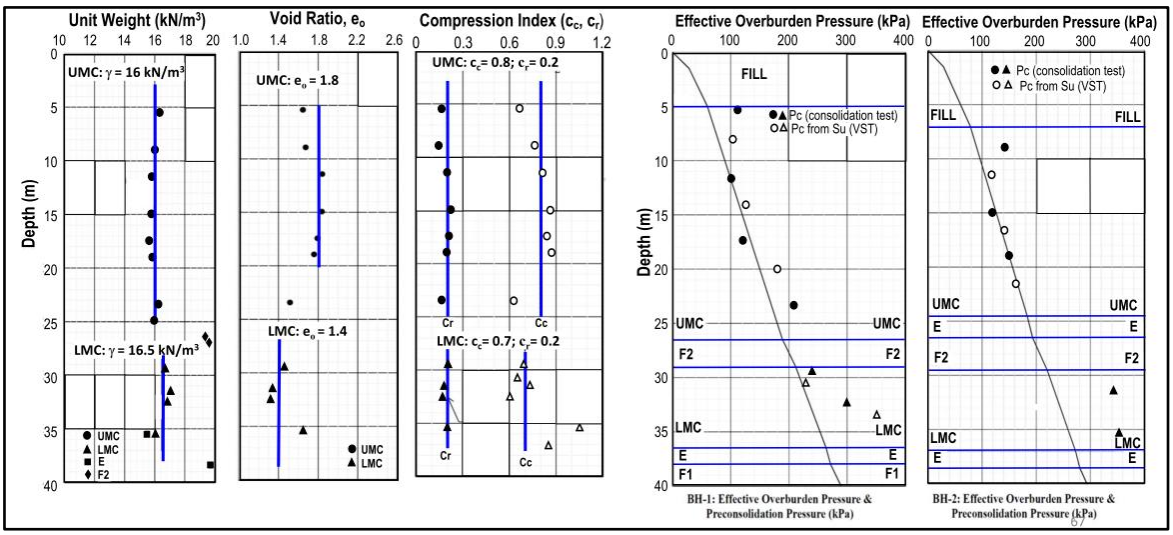

Figure 8: Consolidation Properties of Marine Clay

Modulus of Elasticity (E): The undrained modulus of elasticity (Eu) were estimated from undrained shear strength, Cu as follows:

$$Eu = \alpha\ Cu$$

Where α: Eu/Cu coefficient derived from Figure 9 based on plasticity index (Ip) and OCR

The ranges of Ip (liquid limit, LL – plastic limit, PL) were varying from 35 to 42 with an average of 39 for the upper marine clay layer and varying from 31 to 40 with an average of 36 for the lower marine clay layer. The coefficients α (Eu/Cu) are computed to be 420 using upper bound Ip of 42 for UMC and 465 using average Ip of 39 for UMC. Based on the above, the Eu/Cu values are proposed to be 400 for the characteristic Eu and 450 for the most probable Eu. The characteristic and most probable design parameters for the Kallang Formation derived from the field and laboratory tests for the OM design are summarized in Table 3.

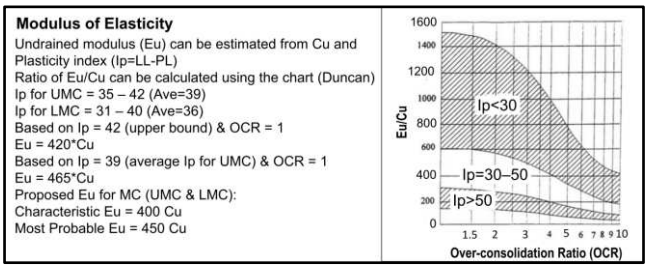

Figure 9: Undrained Modulus (Eu) of Marine Clay Estimated from Cu and Ip (Duncan and Buchighani)

Geology / Strata		Unit Weight (kN/m³)	Undrained Shear Strength, Cu (kPa)		Effective Shear Strength		Modulus of Elasticity, E (Mpa)	
			CS	PS	c' (kPa)	ϕ (°)	CS	PS
Fill		19	–	–	5	30	10	15
Kallang Formation	Upper Marine Clay (UMC)	16	28 (z<GL-13m) 28+1.5(z-13) (z>GL-13m)	35 (z<GL-17m) 35+2(z-17) (z>GL-17m)	–	–	400Cu	450Cu
	Lower Marine Clay (LMC)	17	55 (z<GL-33.5m) 75 (z>GL-33.5m)	55 (z<GL-33m) 80 (z>GL-33m)	–	–	22 (z<GL-33.5m) 30 (z>GL-33.5m)	25 (z<GL-33.5m) 36 (z>GL-33.5m)
	Estuarine Clay, E	15			–	–		
	E1 (above LMC)		55	60			22	27
	E2 (below LMC)		75	80			30	36
	Fluvial Clay, F2	19	100	110	–	–	50	55
	Fluvial Sand, F1	19	–	–	0	32	–	–

Note: z denotes depth below ground; N denotes SPT N-values
CS: Characteristic strength; PS: Most probable strength

Table 3: Geotechnical Design Parameters for Fill and Kallang Formation

5. OM Design and Analyses

The OM design required two sets analyses to be submitted for authority approval using the characteristic design parameters for the Characteristic Scenario (CS) and the most probable design parameters for the Probable Scenario (PS). Except for the design parameters, the other design conditions for the ERSS would be the same for both scenarios. Based on the derived parameters and the construction sequences stipulated in Figure 3 for both scenarios, the analyses were carried out to develop the OM design zones based on the estimated ERSS wall deflections. The estimated ERSS wall deflections for various construction stages and the development of the OM design zones are presented in Figure 10. The OM design zones were derived from the estimated ERSS wall deflections for both CS and PS. The OM Implementation Level (OMIL) in PS was proposed to be approximately 0.8 of the OM Design Level (OMDL).

Other than the wall deflections, the results of various design components for the ERSS including bending moment and shear forces of the ERSS wall and the strut loads were also computed. The ERSS wall and struts were designed based on the more critical loadings of the two scenarios so that the decision to go for CS or PS would be applicable without needing for additional measures when the monitoring results fall within one or both scenarios. The structural design of the ERSS wall is illustrated in Figure 11 where the bending and shear capacities covered the envelops of both scenarios. The forces trend is generally in line with the deformation profile plotted for the two (2) scenarios. The maximum bending moments from the envelope of the PS occurs slightly earlier compared to the CS case due to absence of the third layer of struts in the CS case. In terms of magnitude of the governing maximum forces in the wall, the forces are close between the two scenarios with some tapering down of the Bending Moments from the FEL downwards towards the toe consistent with its earlier reversal of the bending curvature.

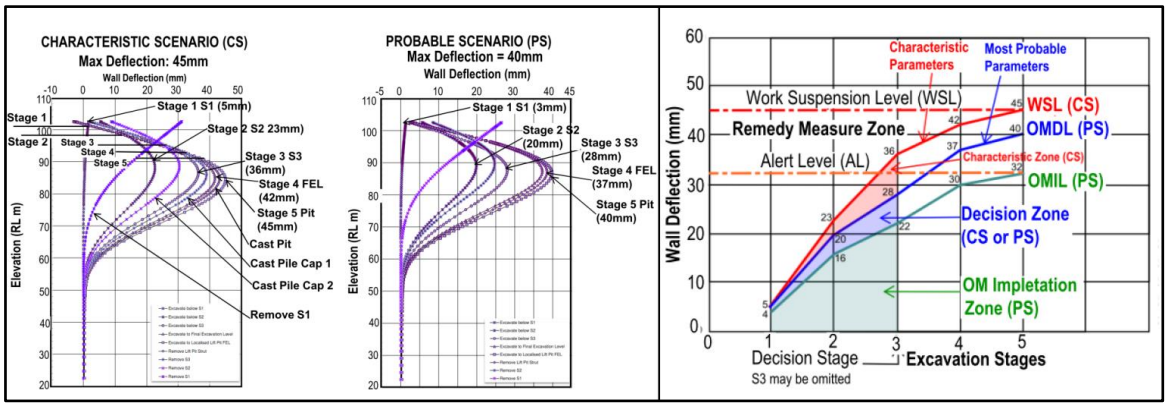

Figure 10: ERSS Wall Deflections and Development of OM Zones

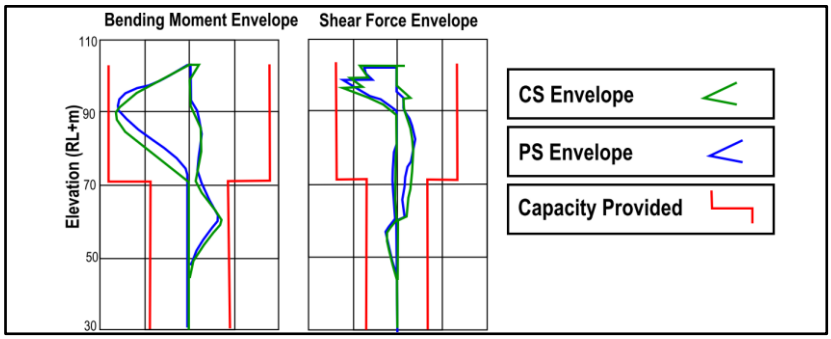

Figure 11: Bending Moment and Shear Forces Envelopes for CS and PS

6. Performance of ERSS and Implementation of OM

Instrumentation and Monitoring: Extensive instrumentation and monitoring have been carried out to monitor the performance of the ERSS as well as the adjacent structures. The instrumentation for monitoring of the ERSS included: (a) in-wall inclinometers at typically 25m intervals; (b) in-ground instruments including inclinometers, water standpipes and piezometers; (c) strut monitoring using vibrating wire strain gauges (VWSG); and (d) ground settlement markers. Instruments for monitoring of the adjacent structures included: (a) extensive automated monitoring system (ATMS) for monitoring of adjacent RTS structures and a service tunnel; (b)

building settlement markers and tiltmeters for monitoring of the settlements and differential settlements of the adjacent buildings due to the construction works; and (c) monitoring of the adjacent utilities and services.

Performance of ERSS: The instruments were closely monitored during the progress of the excavation. At Stage 2 excavation (excavation to 2nd level strut), the wall deflections were measured to be less than 10mm (maximum about 6mm) which was far less than the estimated 23mm for CS and 20mm for PS. There were insignificant increases in the wall deflections for the excavation to Stage 3 (OM decision stage). The maximum wall deflections measured from in-wall inclinometers were still be less than 10mm compared to the estimated values of 36mm and 28mm for CS and PS, respectively. The measured strut loads showed that there were insignificant changes in the strut loads after pre-loadings on the struts were carried out. Monitoring of the surrounding structures were also showing negligible movements. Therefore, the decision to omit the 3rd level struts were made. Further excavation to the formation level of the basement and for the pit were carried out without installing the 3rd level struts. The increases in the wall deflections were slight to negligible with the maximum wall deflection measured at less than 20mm. After completion of the pit, the casting of the pile cap and strut removal were carried out smoothly with significant time and cost saving compared to CS scenario. There were insignificant changes in the ERSS wall deflections during the strut removal stages.

The results of the in-wall inclinometer readings after completion of the basement are presented in Figure 12 together with the strut monitoring results. The ERSS wall deflections at various stages of construction are plotted together with the OM design levels in Figure 12.

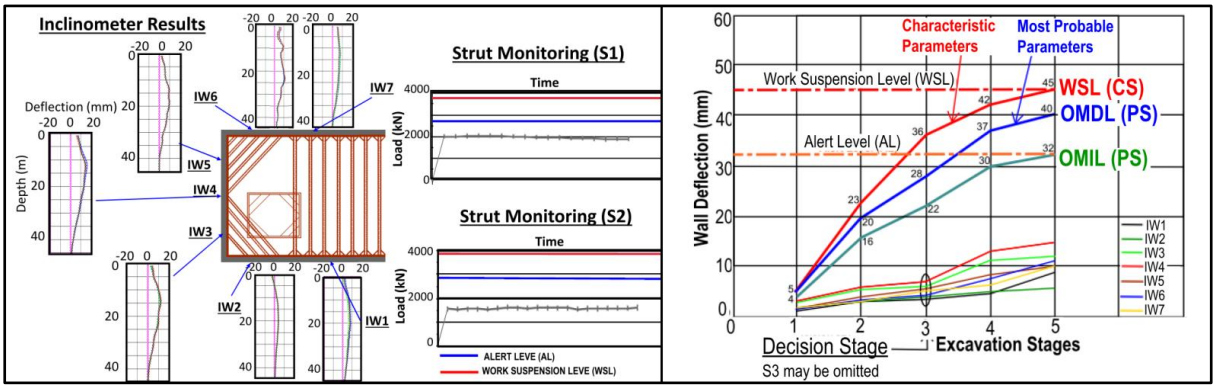

Figure 12: Instrumentation Results and Implementation of OM

7. Conclusion

The Observational Method (OM) had been adopted for the basement construction following the guideline of the OM framework launched by the Building and Construction Authority (BCA) of Singapore. The OM design had been carried out using Characteristic parameters for the Characteristic Scenario (CS) and using Most Probable parameters for the Probable Scenario (PS). Three levels of struts are required for the CS scenario and two levels of struts for the PS scenario.

From the instrumentation and monitoring results during construction, the measured ERSS wall deflections were well below the OM design levels and the OM was successfully implemented. The direct outcome of the successful OM implementation was enabling the removal of the otherwise required 3rd level of strutting installation. This had resulted in direct material and labour cost savings with time savings required from the supply and installation of this 3rd layer of steel strutting over and above the preceding two layers of steel strutting above. Beyond the said direct cost and time savings, this approach had enabled increased productivity of the overall sub-structure construction due to the direct access afforded to the bottom most volume of the basement construction with a much more generous headroom to enable the construction works at this last section relatively unencumbered resulted in increased productivity and three months savings in the construction program. In conclusion, the implemented Observational Method had realized an optimized ERSS works design for this project in a well-thought safe manner as verified by the actual instrumentation readings and the successful completion of the overall sub-structure construction.

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