Open Cut Excavation Observational Method Associated with 3D Analysis for HKBCF PCB

A. Martucci* & A. Pickles

Golder Associates (HK) Ltd.

*Corresponding author
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Abstract

The design of open cut excavations in newly reclaimed land overlying soft soils is often highly sensitive to the undrained strength parameter values. Under such circumstances, the use of the Observational Method may introduce significant programme and quantity savings by allowing the designer to adopt best estimate, rather than moderately conservative parameters. The Hong Kong Boundary Crossing Facilities (HKBCF) is located on newly reclaimed land located to the East of Chek Lap Kok Island. The Passenger Clearance Building (PCB) is located in the middle of the HKBCF and provides the customs and immigration facilities for passengers entering Hong Kong from the Hong Kong-Zhuhai-Macau Bridge and the Tuen Mun-Chek Lap Kok Link. The construction of the PCB basement required an excavation of approximately 10 m depth over an area of approximately 200 by 200 m. The typical soil profile consists of 15 m of sand fill overlying 20 m of very soft to soft Marine Clay. Ground improvement with prefabricated drains and surcharge was adopted by the reclamation Contractor to improve the Marine Clay strength. Extensive ground investigations indicated that the Marine Clays had not been fully consolidated at the time of the excavation work and the majority of the clays were still significantly weaker than anticipated. The low strength of the Marine Clays posed a stability related challenge to the design of the basement excavation. The standard design approach based on 2D stability analyses would have required extensive ground treatment to be carried out to improve the clay by, for example, cement injection (i.e. jet grouting or deep soil mixing). However, an innovative open cut solution was developed, using 3D modelling associated with observational method, taking advantage of the particular basement geometry to fully account for the 'edge effects', which increase the excavation stability when the excavation is of limited extent.

Keywords: Observational method, 3D analysis, Excavation

1 Introduction

The infrastructure for the Hong Kong Boundary Crossing Facilities (HKBCF) is constructed on newly reclaimed land located to the east of the Hong Kong International Airport at Chek Lap Kok island. The HKBCF serves as a transportation hub connecting Lantau Island and the Hong Kong International Airport (HKIA) with the Hong Kong-Zhuhai-Macau Bridge (HKZMB) and the Tuen Mun-Chek Lap Kok Link (TMCLKL). The Passenger Clearance Building (PCB) provides the customs and immigration facilities for passengers entering Hong Kong from the HKZMB. Aerial view photo of the PCB and the HKBCF is presented in Figure 1.

Construction of the PCB basement required a 9.5 m deep excavation in Fill overlying very soft to firm Marine Clay. The design of the excavation was optimised using the observational method, associated with detailed 3D modelling of the excavation sequence.

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This paper describes the design philosophy adopted for the open cut observational method adopted. The excavation performance is assessed with reference to the benefits achieved with the implementation of the observational method and comparison of predicted soil movement against monitoring data.

Figure 1: Aerial View of PCB (https://www.hzmb.gov.hk/en/info/photo-hkbcf.html)

2 Project Description

The PCB comprises of a 2 level high podium structure with a roof cladding system and basement, occupying a footprint of approximately 200mx200m in plan. The building is founded on a system of reinforced concrete pilecaps and beams, supported by large diameter bored piles founded on rock. The construction of the foundations required an excavation of approximately 9.5 m depth to a final formation level of approximately -4 mPD. This paper focuses on the excavation of the western portion of the basement, where very soft Marine Clay was encountered below the reclamation fill.

3 Subsoil Conditions

The geological profile across the site has been altered by the reclamation works undertaken in the area to form the HKBCF island. The site formation level after surcharge removal is at +5.5 mPD. The reclaimed land was constructed using sand fill placed directly over soft marine clay improved with Prefabricated Vertical Drains (PVD). Surcharging was applied to accelerate consolidation. The geological profile after reclamation consists of 5 main layers:

e) Fill – typically medium dense to dense sand
f) Marine Deposit – typically very soft to firm silty clay
g) Alluvial Deposit – typically interbedded layers of firm to stiff silty clay and medium dense to very dense silty clayey sand
h) Completely and Highly Decomposed Granite (C/HDG)
i) Moderately Decomposed Granite (MDG) or better

A simplified geological section is shown in Figure **5**2

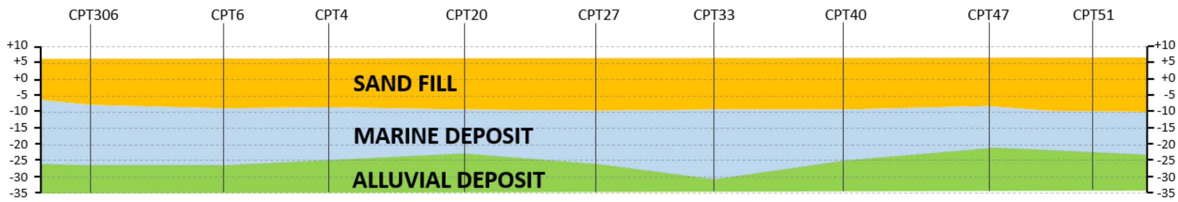

Figure 2: Geological Section

Traditional open cut design is based on adoption of moderately conservative parameters. For the observational method, a second set of most probable parameters is also required. The two sets of parameters adopted for the observational approach are summarised in Tables 1 and 2. It can be seen from Tables 1 and 2 that the differences between the moderately conservative and most probable parameters are limited to the strength and stiffness of the marine clay and the stiffness of the fill and alluvial deposits, as these are the parameters that control both the stability of the excavation and the predicted movements of the ground.

Table 1. Summary of Moderately Conservative Soil Parameters

Geological Stratum	γ_{sat} (γ_{unsat}) [kN/m^3]	Cu [kPa]	c' [kPa]	ϕ' [°]	Eu [kPa]	E' [MPa]
Vibrocompacted Fill above +1.0 mPD	20.0 (17.5)	-	0	37	-	15
Uncompacted Fill below +1.0 mPD	19.5 (16.5)	-	0	35	-	15
Marine Deposits	16.5	Refer to Figure 4	0	25	350 x Cu	-
Alluvial Deposits	18.5	60 + 5.0 x d	0	28	350 x Cu	-

d is depth below -34 mPD

Table 2. Summary of Most Probable Soil Parameters

Geological Stratum	γ_{sat} (γ_{unsat}) [kN/m^3]	Cu [kPa]	c' [kPa]	ϕ' [°]	Eu [kPa]	E' [MPa]
Vibrocompacted Fill above +1.0 mPD	20.0 (17.5)	-	0	37	-	25
Uncompacted Fill below +1.0 mPD	19.5 (16.5)	-	0	35	-	25
Marine Deposits	16.5	Refer to Figure 4	0	25	460 x Cu	-
Alluvial Deposits	18.5	60 + 5.0 x d	0	28	200 x10^3	-

d is depth below -34 mPD

3.1 Marine Deposits Undrained Shear Strength

The undrained shear strength (Cu) of the Marine Deposits is the critical parameter with regards to the stability of the open cut. Extensive ground investigations were carried out to determine the nature and variability of the clay across the site, mainly by boreholes, Cone Penetration Tests (CPT) and Vane Shear Tests (VST), as shown in Figure 3.

The western portion of the basement (denominated Area W in Figure 3) is where the weakest Marine Deposits were encountered, with typical values between 10 and 50 kPa. A significant degree of variability is identified from the available GI. The moderately conservative and most probable design lines were determined based on CIRIA C580 definition, corresponding approximately to values with approximately 75% and 50% probability of exceedance, respectively. Figure 4 shows the adopted strength profiles.

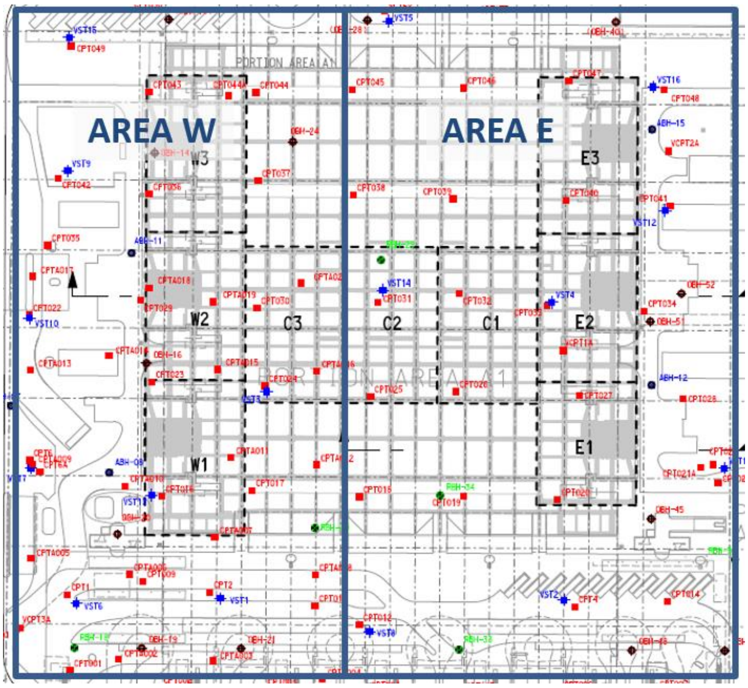

Figure 3: Marine Deposits Strength Zoning

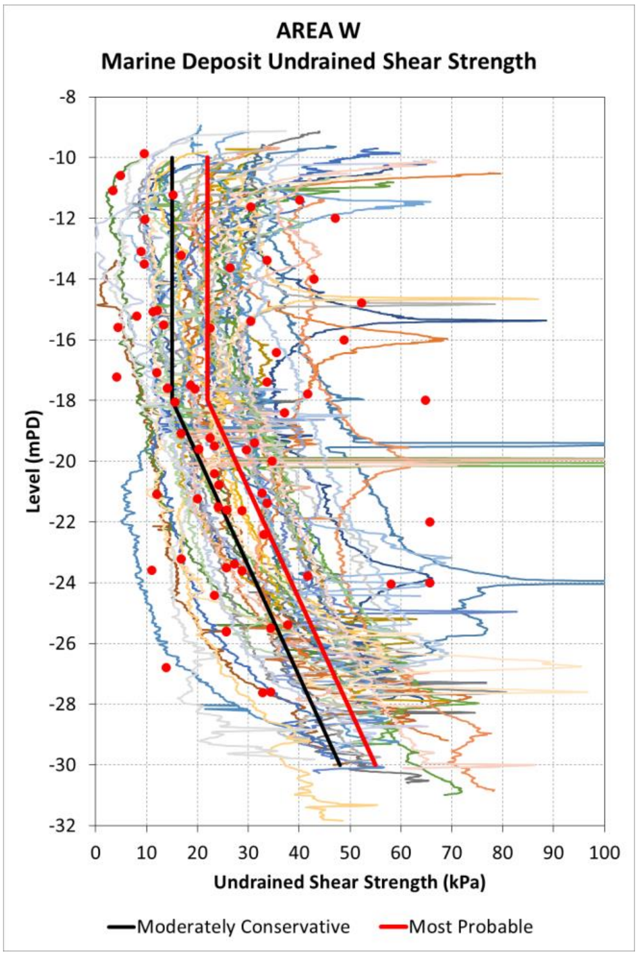

Figure 4: Marine Deposits Undrained Shear Strength at Area W

4 Open Cut Excavation Design

4.1 Introduction

The basement excavation was carried out in a staged manner starting from the south-east corner and progressing towards the north-west. The eastern portion (Area E) of the basement was located over an area with stronger Marine Deposits, whilst the most challenging conditions were encountered at the western portion.

Traditional design using moderately conservative parameters and 2D stability analysis was found to be adequate for Area E. 3D analyses associated with the observational method using most probable parameters were instead implemented to optimise the excavation design at Area W. The overall excavation sequence is presented in Figure 5, this paper focuses on Stages 5 to 12 for the western half of the basement.

Adoption of 3D analyses allows for consideration of three-dimensional failure modes which, in most cases, results in more realistic and less conservative FoS than 2D analyses (Zhang 1988; Michalowski 2010). This is because 3D failure surfaces typically have so-called spoon or bowl shape failure mechanisms, whilst 2D surfaces extend in one dimension (i.e. plane strain) and therefore there is no contribution from shear resistance in the orthogonal direction.

The three-dimensional analyses took advantage of the particular geometry of the basement. The contribution of three-dimensional effects was further enhanced by developing a sequence to limit the excavation front extents.

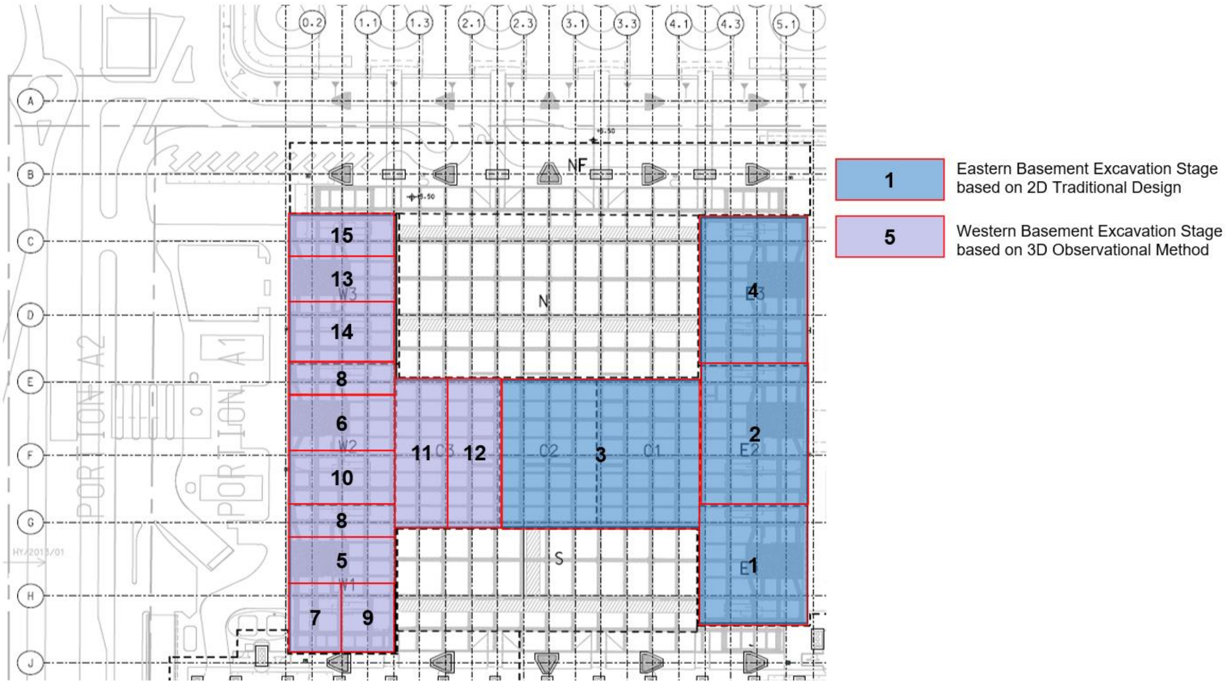

Figure 5: Excavation Sequence

The observational method was implemented based on the recommendations set out in CIRIA 185 (Nicholson et al. 1999) and CIRIA C580 (Gaba et al. 2003). At its core, the observational method involves the adoption of most probable soil parameters, associated with a strong emphasis on monitoring of the excavation performance, to continuously compare predicted with measured soil movements.

The Observational Method is a more rational design and construction method than the traditional approach for a number of reasons as follows:

- The Observational Method allows for a more efficient and cost-saving design proposal to be adopted which is less wasteful and not designed to an overly conservative factor of safety.
- The Observational Method requires risk-sharing, integration and cooperation between the supervising officer, designer and site construction team. This is necessary to reach agreement to change the construction sequence in response to the observed soil movement and excavation performance.
- Typically, a more extensive monitoring programme is required compared with traditional design, which requires increased density of instrumentation to be installed. However, greater attention is paid towards the monitoring works on site which results in improved control of design uncertainties. This inevitably leads to greater understanding of the design requirements and fosters a safer working environment.
- The use of the observational approach does involve additional costs for monitoring works but these are more than offset by the construction cost and time savings. As the observational approach requires some flexibility in the construction program, it is usually more appropriate for the contractor to propose and adopt such an approach, otherwise fairly significant changes may be required to contract documents.

A minimum global FoS > 1.3 was adopted. This value is somewhat higher than required by the HK Ports Works Manual but is more appropriate for conditions which are controlled by the undrained strength of the ground.

4.2 Implementation of 3D Analyses

Preliminary design analyses for the Area W open cut were carried out with standard 2D Finite Element methodology. The analyses indicated that two intermediate benches of 60 and 40m width would be required between the formation level at +5.5 mPD and the final excavation level at -4.0 mPD to achieve the minimum required FoS. A typical failure surface determined from 2D analyses is presented in Figure 6. The failure mode involves an extensive horizontal surface of the order of 100m length with the Fill sliding on top of the soft Marine Clay. This slope profile was considered impractical as the width of the required benches would significantly increase the excavation volumes and the crest of the slope would extend beyond the site boundary.

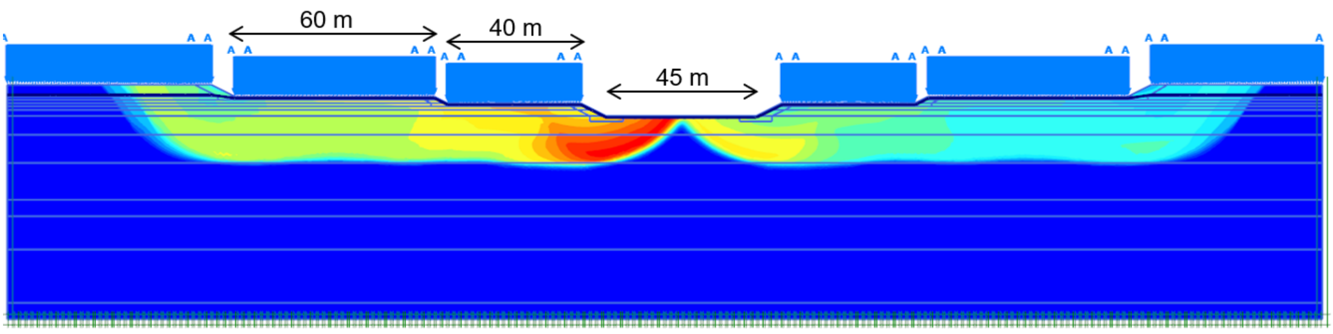

Figure 6: Failure Surface for 2D analysis at Area W

A ground improvement solution was then studied to minimise the excavation volumes. Figure 7 shows the extent of ground improvement, using deep cement mixing or equivalent method, required to achieve a sufficient FoS using 2D analyses and moderately conservative parameters. The scheme would have required continuous ground improvement 'panels' embedded into Alluvial Deposits beneath the slope toes, connected by a thinner ground improvement 'slab' across the basement, enabling a 1:2 single slope from formation to final excavation level. A replacement ratio (ratio between the treated soil plan area and the total plan area) of approximately 50% was envisaged. Whilst a ground improvement solution would have been effective in optimising the excavation volumes, the extent of required ground improvement would have been significant, given the size of the basement.

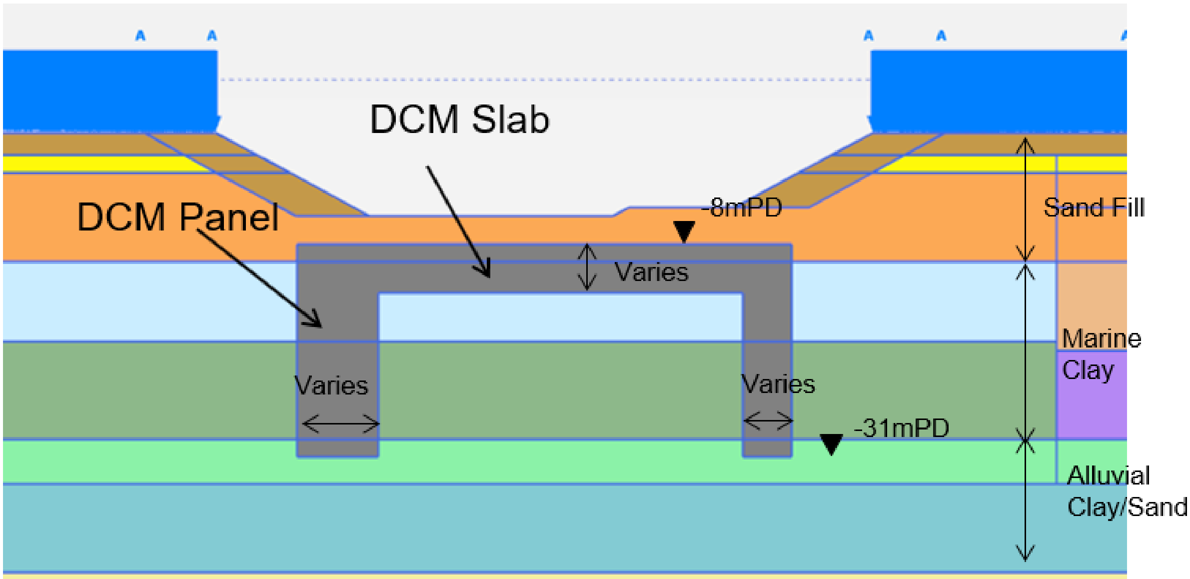

Figure 7: Potential Ground Improvement Solution

Therefore, in order to achieve a more rational and sustainable design, an innovative open cut design based purely on three-dimensional stability considerations, without requirement for any additional ground improvement, was developed. By using 3D analyses it was possible to significantly reduce the excavation volumes, adopting a single intermediate bench of 25 m width at +2.0 mPD and 1:2 gradient slopes, as shown in Figure 8. This design was based on moderately conservative parameters.

The open cut stability in a three-dimensional analysis is sensitive to the extent of the excavation, therefore a specific sequence was developed, dictated by the objective to limit the extent of the open cut front in order to maximise the three-dimensional effects.

As the excavation front progresses, portions of the basement foundations are required to be installed, as the pilecaps and beams provide additional constraints to the potential failure surfaces, thereby increasing the stability of the excavation.

As an example, with reference to the sequence shown in Figure 5, the excavation in Area W commenced at the two Zones 5 and 6 first. Before the adjacent Zones 7 and 8 could be excavated, it was required to install the foundations in both Zones 5 and 6. Similar constraints were necessary for the remainder of the excavations sequence, as summarised in Table 3.

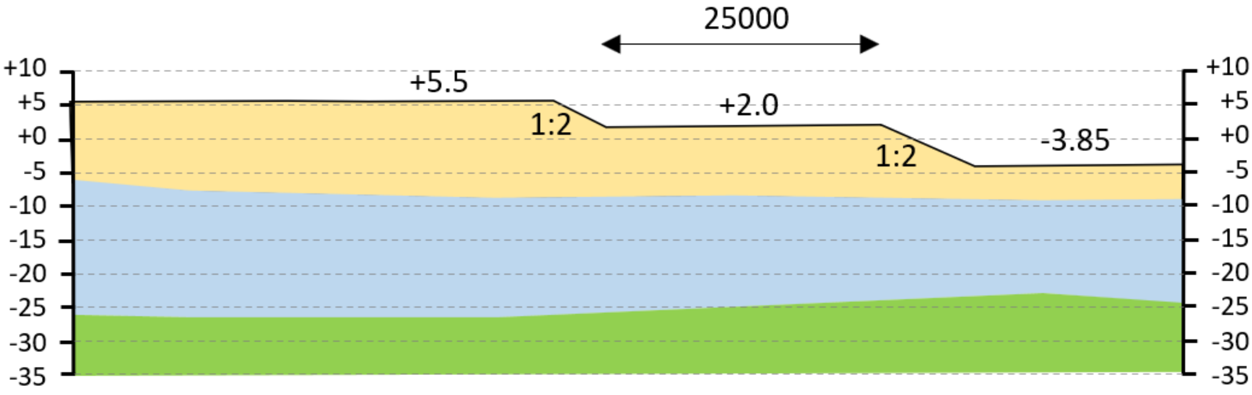

Figure 8: Open Cut Profile for Area W

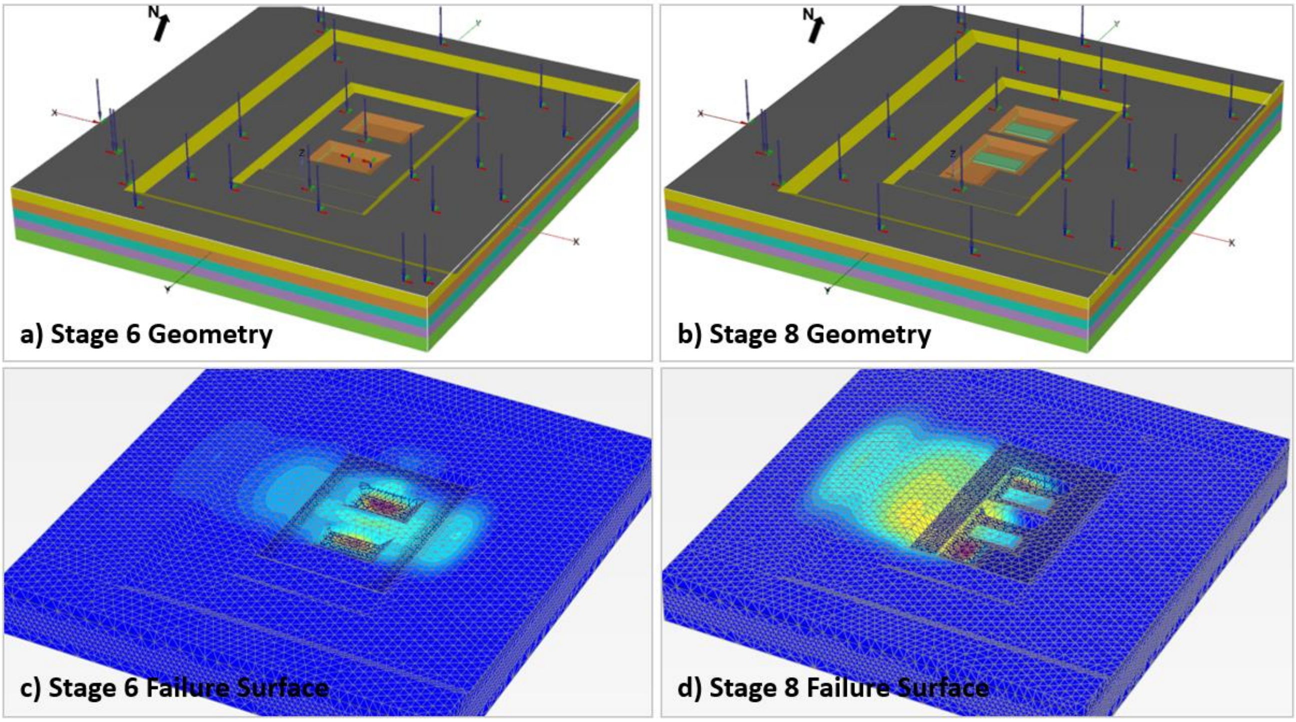

Figure 9: 3D Analysis for Stages 2D and 3D Based on Moderately Conservative Parameters

Table 3. Comparison of Foundations Construction Requirements

Excavation Area	Foundation Construction Requirements Moderately Conservative Parameters - Areas	Foundation Construction Requirements Most Probable Parameters - Areas
5	None	None
6	None	None
7	5	None
8	5, 6	None
9	5, 6, 7	None
10	5, 6, 7, 8	5
11	5, 6, 7, 8	5
12	5, 6, 7, 8, 10	5, 6

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13	5, 6, 7, 8, 9, 10, 11, 12	5, 6, 8
14	5, 6, 7, 8, 9, 10, 11, 12, 13	5, 6, 8
15	5, 6, 7, 8, 9, 10, 11, 12, 13, 14	5, 6, 8

4.3 Implementation of Observational Method

The observational method was developed for the Area W excavation before the commencement of the excavation in these areas (‘Ab Initio’ approach).

Application of the ‘Ab Initio’ approach was possible because sufficient data on the performance of the Area E excavation was available from inclinometers and ground movement markers was available as Stages 1 and 2 of the sequence, which correspond to the south-east corner of the basement had been completed.

The available monitoring data was used to carry out a back-analysis using 3D modelling and most probable soil parameters based on available GI data. Figure 10 presents the ground movements predicted by the Plaxis 3D model against the lateral movement monitored by the inclinometer adjacent to the slope crest after completion of the excavation to final formation level within Stages 1 and 2 zones.

One of the key findings of the back-analysis was that the Alluvium behaved in a stiffer manner than expected, likely because this layer is outside the influence depth of soil movements induced by the excavation unloading. In order to match the measured movements, the Young’s modulus of the Alluvium was increased from approximately 20 MPa to 200 MPa, which is representative of a small strain stiffness of the alluvium.

The stiffness of the Marine Deposits and the Fill were also slightly increased by 30% and 67% respectively.

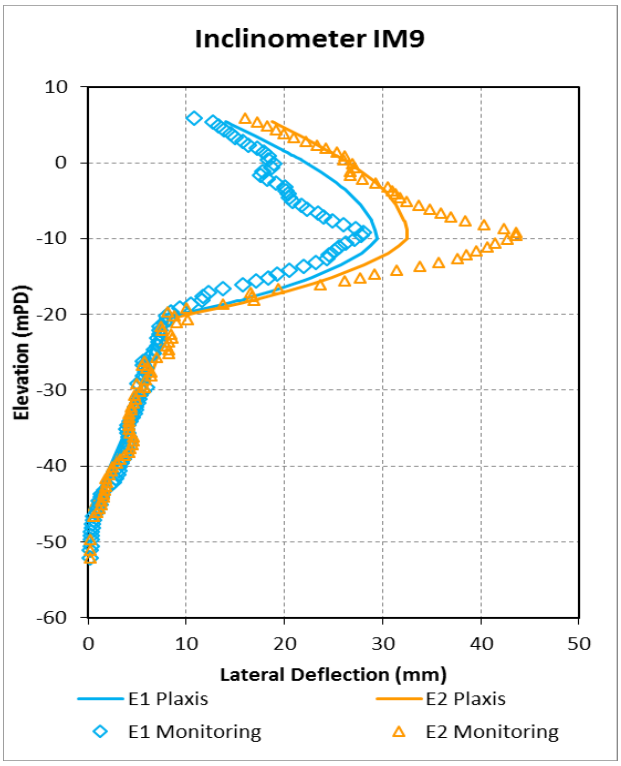

Figure 10: Results of Open Cut Back Analysis for Movement after Completion of Stages 1 and 2 Excavation

In accordance with the observational method framework, an optimised sequence was developed using most probable parameters to accelerate the programme with comparison with the sequence determined using moderately conservative parameters. Both sequences followed the same excavation stages, generally progressing from the south towards the north from Stage 5 to 15 (stages 1 to 4 refer to Area E) and the same open cut profile with 25m wide bench at +2.0 mPD. The key difference introduced in the Observational Method sequence is a significant reduction in the requirements for construction of foundations pilecaps and beams, in order to speed up the temporary excavation progress. Table 3 shows a comparison of foundation construction requirements according to the moderately conservative and most probable sequences.

It is clear how the successful implementation of the observational method would enable the contractor to delete the majority of basement construction requirements and speed up the excavation programme.

A relatively extensive set of monitoring instrumentation was proposed to control the observational approach. In order to target the instrumentation work in the most efficient manner, the instruments were split into three categories:

- Critical - a limited number of instruments which are directly adjacent to the area being excavated. These instruments were considered the most relevant to assess the excavation safety and performance and were monitored twice a day.
- Primary - the rest of the instruments surrounding the basement and located close to the open cut slope crest. These instruments were monitored on a daily basis.
- Secondary - all other instruments within 50 m of the ongoing excavation work. These instruments were monitored at least two times per week.

A plan of the proposed instrumentation to monitor the excavation performance is shown in Figure 11. A total of 23 inclinometers at approximately 15m spacing and 24 soil movement markers were installed for the Area W observational method monitoring.

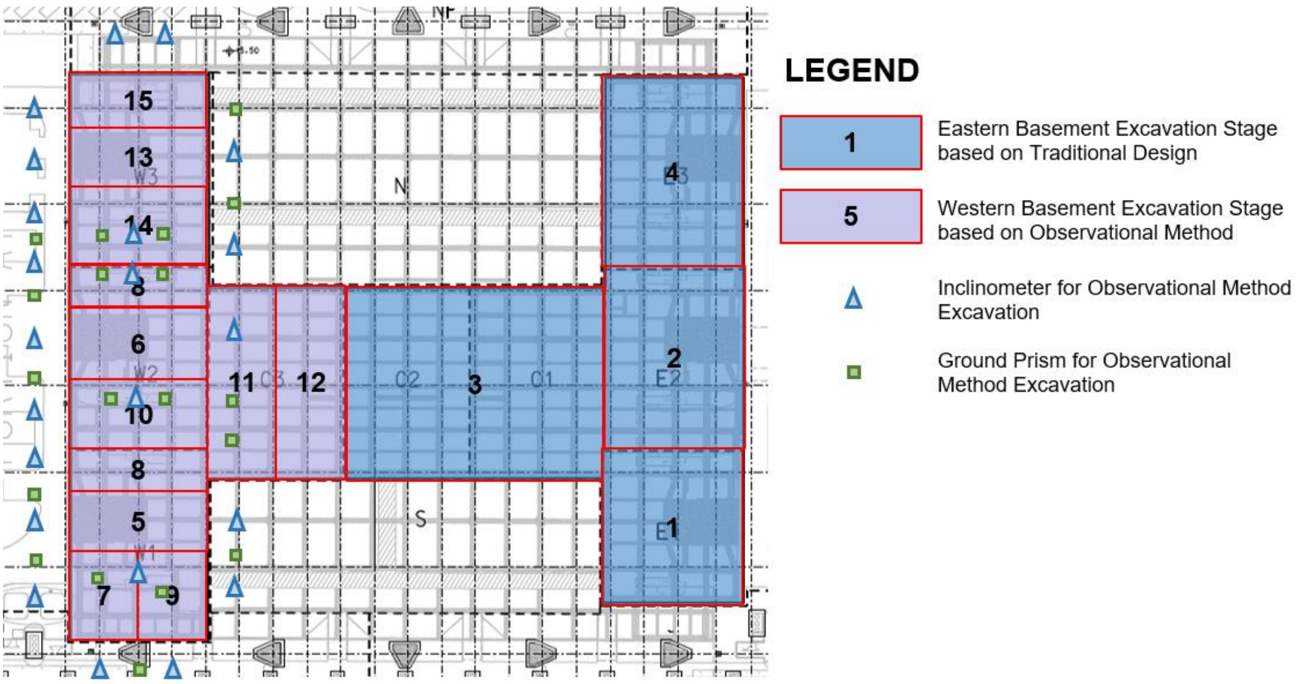

Figure 11: Monitoring Plan

The excavation performance was assessed with reference to Trigger Levels for soil lateral movement and soil shear strain levels measured from the inclinometer data.

Soil movements Trigger Levels were based on design predictions at each stage and at each inclinometer location for both most probable and moderately conservative sequences as follows:

a) Amber Trigger – Corresponds to the ground movement prediction using most probable parameters, 10 kPa surcharge load and a groundwater level of -1.0 mPD which was based on the measured levels in observation wells in Area W. The low water level is a result of the ongoing dewatering.
b) Red Trigger – Corresponds to 80% of the ground movement prediction using moderately conservative parameters, 10 kPa surcharge load and a robust groundwater level of +1.5 mPD.

The factor of 80% applied for the red trigger is to take into account the condition that the soil movements may not occur instantaneously during the excavation works due to the presence of soft undrained material. The ground may instead exhibit 'creep behaviour' with increase in movements over time, even if no further excavation works are carried out.

Shear strain trigger levels, determined from the inclinometer profiles, were also adopted in order to overcome the uncertainty caused by variations of the ground profile and soil stiffness, which may affect the magnitude of predicted movements, as follows:

- Amber Trigger – Maximum shear strain of 1%
- Red Trigger – Maximum shear strain of 2%

Soft clays are considered to reach approximately 80 to 90% of peak stress capacity at shear strain levels of the order of 3 to 4%, therefore it is considered prudent to monitor the stability of the excavation against a maximum allowable shear strain of 2%. These shear strain Trigger levels are considered to represent the most objective way of determining the stability of the excavation, as they are not sensitive to the soil strength and stiffness design assumptions.

The observational method framework required that whenever an Amber Trigger is exceeded, a thorough review of the monitoring data is carried out in order to review the movement trends and assess the stability. Ad-hoc actions such as increased monitoring frequency would be required on a case by case basis.

If a Red Trigger is exceeded, any further excavation work would be stopped and contingency measures requiring construction of the foundations in accordance with the moderately conservative design sequence would be applied.

Furthermore, should the ground continue to creep and movements exceed 120% of predicted values, emergency measures would be applied to mitigate the risk of deep seated slope failure. Emergency measures typically required the contractor to backfill the excavation with a minimum of 2 m soil, or until the movements stabilise.

5 Performance Review

Continuous monitoring was carried out to verify the stability and safety of the excavation. The excavation lateral movement measured by the inclinometers were generally in agreement with the design predictions using most probable parameters, which had been used to set the Amber Triggers.

Figure 12 shows the movement profiles for the inclinometers installed at the west of the excavation. The maximum movement occurs towards the top of the Marine clays and was typically of the order of 100 mm, which is slightly larger than the predicted movements.

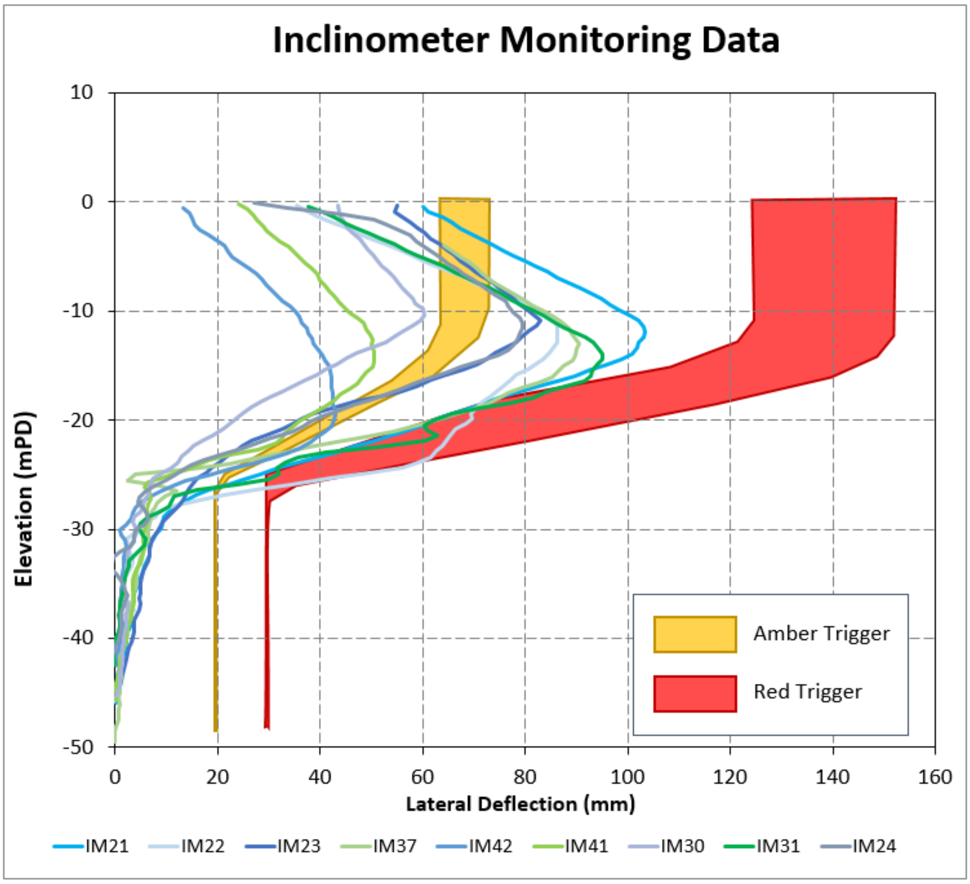

Figure 12: Inclinometer Movement Profiles at West of the Area W Excavation vs Trigger Levels

As indicated from the back-analysis at the eastern portion, the Alluvial Deposits behaved in a relatively stiff manner also for the excavation in the western portion. Above the alluvial deposits, the Marine Deposits exhibit a sharp increase of lateral movement due to shear strains necessary to mobilise the required shear stresses and achieve equilibrium due to the excavation works. Typically, maximum shear strains of approximately 1 to 1.5% (below the red triggers) were determined from the inclinometer profiles.

Of interest is the analysis of the development of the soil movements as the staged excavation progresses. Figure 13 shows the cumulative movement at the top of the Marine Deposits for Inclinometer IM21, which is located at the west of the Stage 5 area, as shown in Figure 14. The plot also includes the Amber and Red triggers determined at this inclinometer location for the different stages based on the design analyses. The largest movement contribution at this location is due to the excavation of the adjacent Stage 5 area, however further incremental movements are predicted as the excavation progresses and, in particular, when the adjacent Stage 6 and 7 areas were completed. The inclinometer data indicates relatively good agreement with the Amber Trigger. However, the soil response appears to initially lag behind the excavation (Stages 5 to 6). After Stages 7/8, ongoing movement is measured after the excavation of all adjacent areas had been completed, albeit with a

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slower rate. This movement is considered to be due to creep of the soft Marine Deposits as this soil responds to the unloading caused by the excavation.

Similar relatively small rates of creep movement were measured generally in all inclinometers, however this tended to stabilise over time as the construction of the basement foundations progressed.

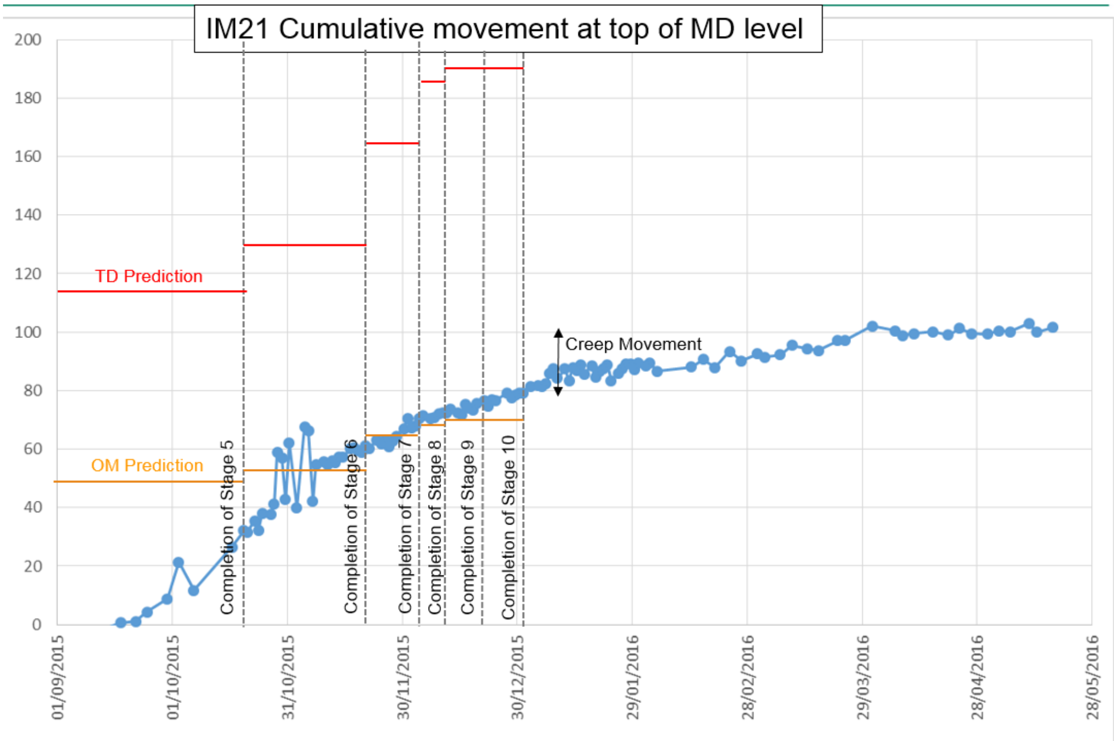

Figure 13: Maximum Inclinometer Movement vs Time

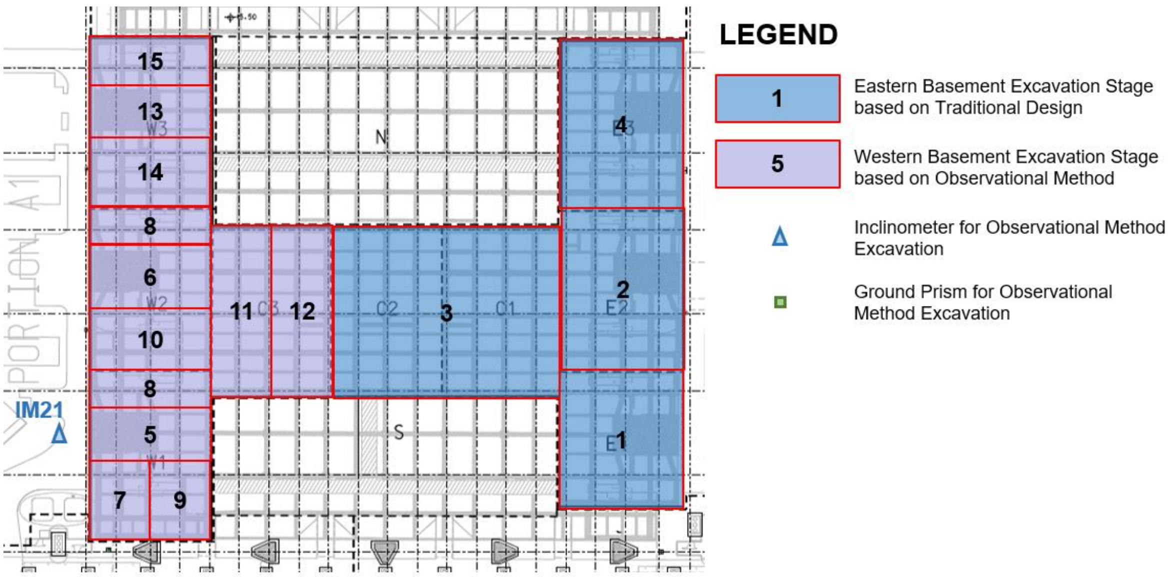

Figure 14: Location of Inclinometer IM21

At the end of each excavation stage, an ad-hoc meeting was held between Designer, Contractor, Independent Reviewer and Client's Engineer to review the stability of the excavation and agree on whether the excavation could progress according to the optimised observational method sequence. The successful implementation of the observational method was only possible thanks to the commitment of all parties to develop and follow the framework, hold timely reviews and promptly reach agreement on whether the most probable sequence could be followed after completion of each excavation stage.

As the performance of the excavation was generally in line with the predicted most probable movement and all the monitoring data was within the red triggers, no contingency measures had to be implemented throughout the works and all the observational method objectives to reduce the extent of foundations construction were achieved. It was estimated that a 2 month saving in excavation programme was achieved by implementing the observational method with comparison to the sequence required if the traditional design had been followed.

6 Summary and Conclusions

The adoption of the observational method associated with 3D stability analyses has allowed the contractor to efficiently complete a large scale open cut excavation in difficult ground conditions where thick very soft clay was present underlying a newly reclaimed land.

The standard design approach based on 2D stability analyses would have required extensive ground treatment to be carried out to improve the clay by cement injection (i.e. jet grouting or deep soil mixing). The 3D excavation design provided an effective and sustainable solution compared to the ground improvement option, which would have required injection of over 14 thousand tons of cement in the soft soils and would cost approximately 12 million US$.

The 3D excavation sequence using moderately conservative design parameters required staged excavation with the pilecaps and ground beams completed before the next stage of excavation could be commenced. This requirement was fairly onerous in terms of construction timing. The observational approach using best estimate parameters demonstrated that the requirement to construct pilecaps and ground beams could be relaxed assuming that the ground performed as expected. This would save a significant amount of construction time.

The performance of the excavation was very close to the best estimate design assumptions, with the majority of the inclinometers indicating lateral movement magnitude between the most probable and moderately conservative predictions. Therefore, by adopting the observational approach, the excavation was successfully completed achieving all the observational method objectives, with a further saving of over 2 months of programme.

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