Engineering Geological Ground Models: Industry Applications for Geotechnical Investigation Planning, Data Acquisition & Appraisal

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Abstract

Adoption of an engineering geological ground model (EGGM) prior to ground investigation, as a conceptual site characterisation approach, empowers users with the capacity to predict subsurface data trends, test assumptions, refine geotechnical inputs and better manage ongoing ground investigations. This approach informs the planning of ground investigation (GI) locations, in-situ testing, and non-intrusive surveys to ensure high-quality, efficient, and cost-effective data yield. This theme is explored using a case study at Manila Bay, in the Philippines, where a ground model was developed for planning and execution of site investigations and to add-value to site characterisation and geotechnical appraisal for nearshore site formation.

Keywords: Ground investigation, Site characterisation, Nearshore, Manila

1 Introduction

1.1 Ground Modelling Using a Ground Risk Management Framework

As part of industry practice, ground models (Parry, 2014) are essential tools for design of scope, scheduling and evaluation of ground investigations for site characterisation and geotechnical appraisal.

The ground modelling approach to site characterisation initiates during the conceptualisation stage of geotechnical projects. This develops further through the construction and operational stages of the project life cycle. Adopting a Ground Risk Management Framework approach (GRMF, Wood & Eddies 2021) provides strategic direction for managing ground-related risk including ground modelling implementation targeting more economic construction (Figure 1). Each stage targets data streams that maximise time, cost, and quality efficiencies using Geo-data to inform on-going geotechnical works. The predictive elements of ground models evolve over time and are best iterated and modelled implicitly to generate value. This approach builds confidence that data used for geotechnical design, construction and management of assets is robust, well informed, and applicable.

This paper explores the construction of a bespoke ground model to plan a CPT site investigation programme, conduct site characterisation and geotechnical appraisal of site formation works for the proposed Manila International Airport (MIA), in the Philippines. The commercial software Leapfrog Works Version 4.0 (Seequent, 2020) was used for digital transformation, analysis, and visualisation.

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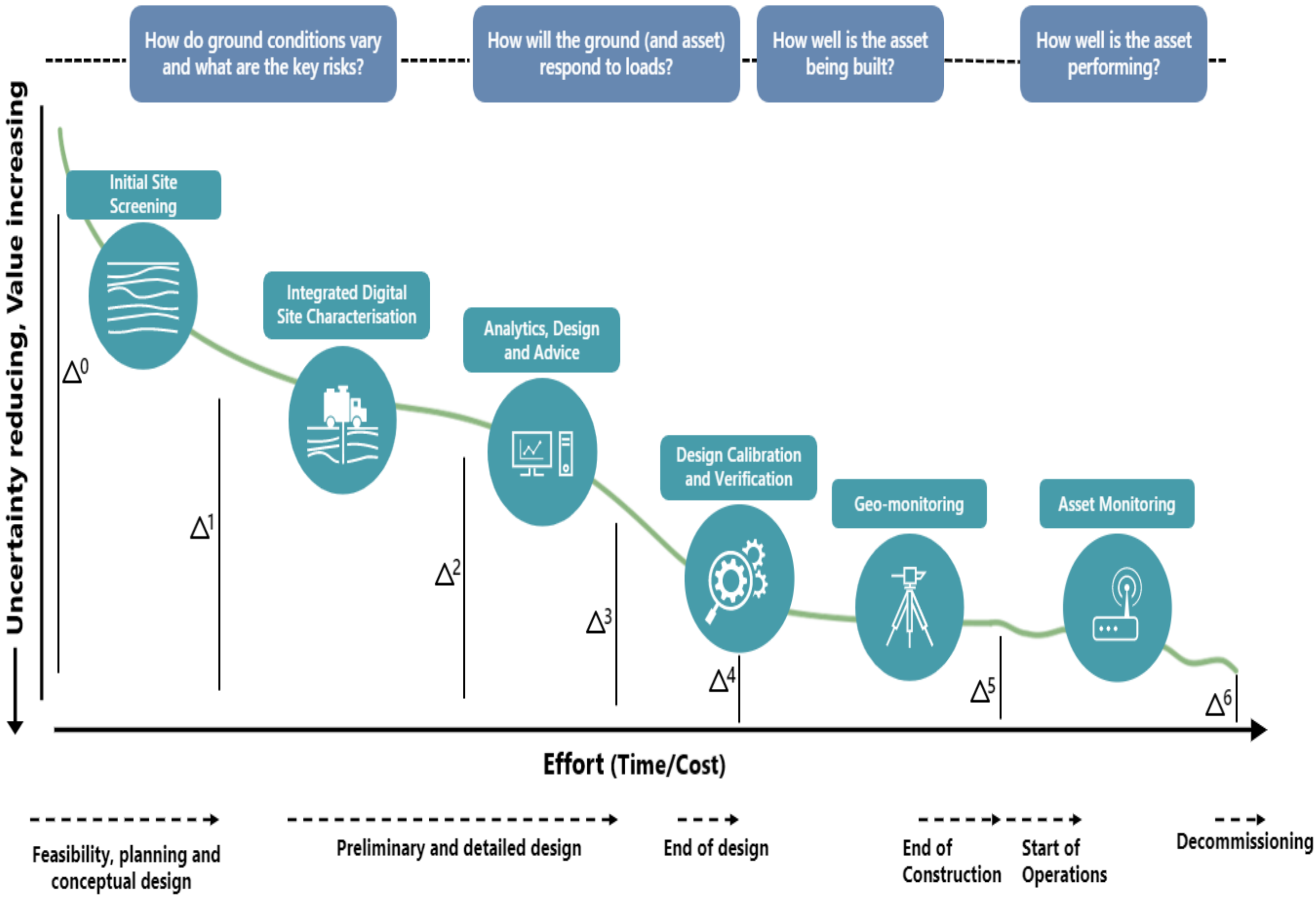

Figure 1: Ground Risk Management Framework (Wood & Eddies, 2021). Along the timeline, Δ^0 represents an initial state, Δ^1 to Δ^6 represent delivery points and data interfaces between cycle phases.

Stages $\mathbf{\Delta}^1$ to $\mathbf{\Delta}^2$ and elements toward $\mathbf{\Delta}^3$ of the Ground Risk Management Framework (GRMF) were implemented (Figure 1) as follows:

- Stage $\mathbf{\Delta}^1$ -existing Geo-data and desktop study information was digitally transformed into a Conceptual Ground Model (CGM) database. This provided geospatial context to the geological and geomorphological setting. Predictive digital surface trends were derived for site screening and informing proposal of CPT locations to fill gaps in the existing information.
- Stage $\mathbf{\Delta}^2$ - CPT records from on-going site investigation were added to the CGM. From a project perspective, the resulting database transitioned into an observational dataset.
  During this stage, the intertidal, deltaic site area was often remote and difficult to access, including human and environmental challenges that restricted data collection. The ground model enhanced the timely relocation of proposed CPT by identifying alternative positions that could test data trends and ensure suitable data yield and quality was suitable to bridge data gaps.
- Transition from Stage $\mathbf{\Delta}^2$ toward Stage $\mathbf{\Delta}^3$ - unique soil sub-units were identified from CPT records. The 3D ground modelling environment helped isolate and visually verify patterns of occurrence. Site teams were informed about the predicted presence of these sub-units to acquire information on their performance and behaviour. The discussions concluded that sub-

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units were persistent across the site and could be targeted for in-situ testing to better understand their geotechnical properties.

- End of Stage **Δ**^{2} & early elements of **Δ**^{3}, the Observational Ground Model (OGM) integrated all qualitative and quantitative data categories. Quantitative values such as cone resistance (q_c), SPT and laboratory test data were compared to qualitative categories such as engineering geological descriptions and CPT soil unit summaries. The additional sub-units identified provided further understanding of the engineering constraints and associated geological influences and constraints. Digital surface trends were used to define geotechnical zones, where patterns of homogeneity in soil geotechnical properties informed geotechnical analyses.

2 Developing the Site-Scale Ground Model to Plan Site Investigations

2.1 Geological & Geomorphological Setting

The proposed MIA is located north of Manila in Bulakan, in Bulacan Province. An initial review of published lithostratigraphy highlighted a consistency with recent experience in existing borehole data within the project regional area. The geomorphological setting comprised Quaternary Plio-Pleistocene-aged Guadalupe Formation, Holocene, and more recent deposits. The Guadalupe Formation makes up the dominant basement unit and consists of upper and lower members, the Diliman Tuff and Alat Conglomerate respectively (AMH Philippines Inc. 2017). The geomorphological setting of the site is characteristic of a broad tidal deltaic river complex, with the Guadalupe Formation being unconformably overlain by sequences of basal shallow-marine clay, mangrove-peat, beach sand, fluvial sand and terrigenous floodplain clay deposits as shown in the schematic cross section (Dell et al. 2001, Figure 2). The site has significant anthropogenic disturbance including the formation of fisheries-related and associated dikes, river training/realignments and intermittent periods of flooding and dewatering. Some initial questions arose during early review:

1) Do the factual records of recent deposits and underlying soil units follow the expected patterns of cyclic and a pro-grading deltaic environment? Can these patterns be tracked and tested during the site investigation to better inform the geotechnical appraisal?
2) Could unique soil sub-units be identified within the overall stratigraphy and can their patterns of occurrence be identified and mapped?
3) Could these sub-units be tested in the field and would their properties be assessed as adverse (introduce design risk), beneficial (reduce design constraints) or benign (no influence) to geotechnical appraisal?

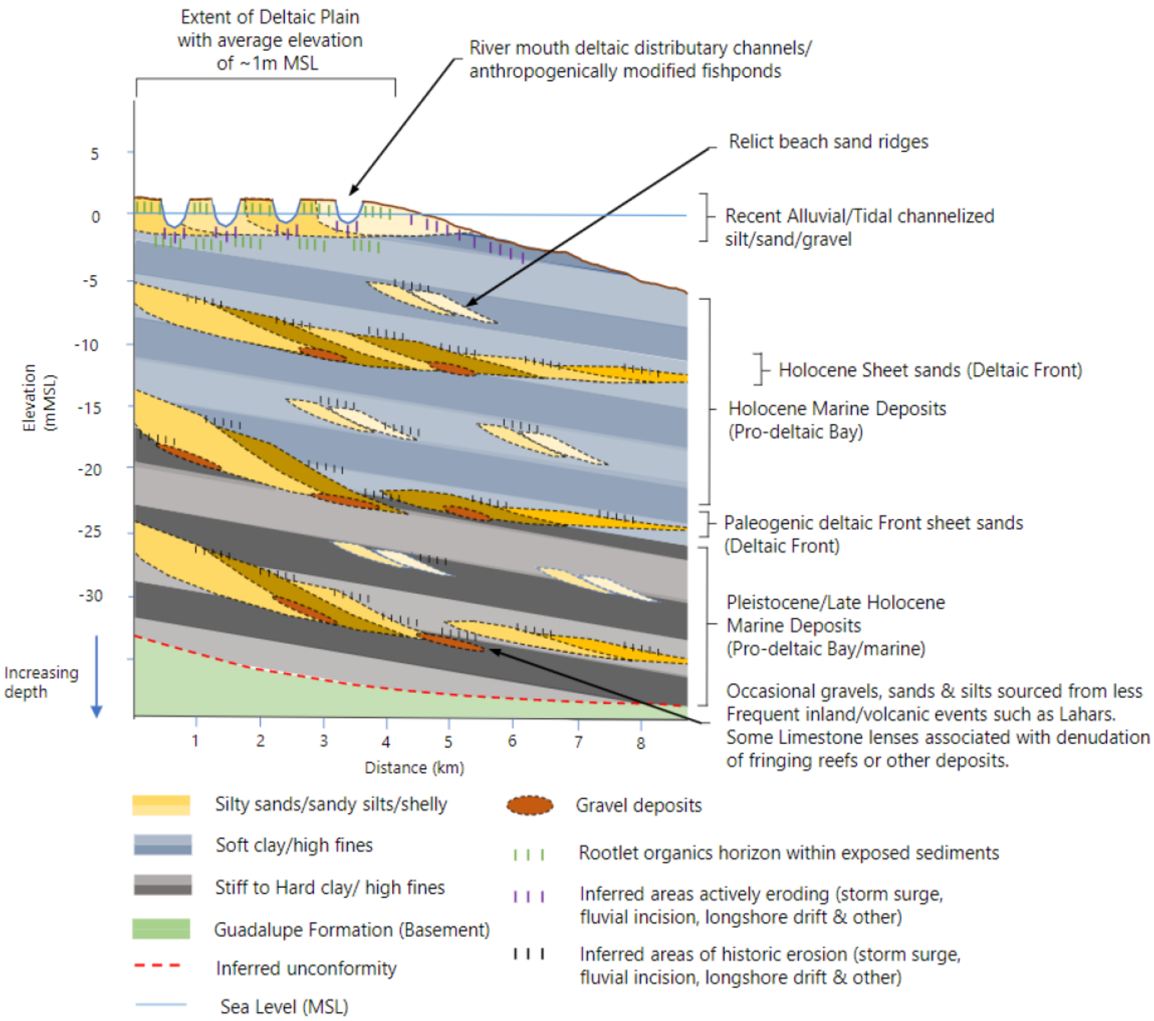

Figure 2: Schematic of general site stratigraphy (Dell et al. 2001)

2.2 The Ground Model Approach Digital Transformation

The Ground Model approach began with digital transformation of soil properties into qualitative (categorical) and quantitative (continuous) data paired with geo-referenced positions (easting, northing and elevation). The schematic of site stratigraphy (Figure 2) guided the interpretative process for the proposed MIA. The depth of interpreted soil interfaces provided base elevation levels for each overlying soil unit. Using a geographical information system (GIS), these data provide point cloud neighbourhoods for mathematical interpolation.

The method of interpolation in Leapfrog Works 4.0 (Seequent, 2020) is the Fast Radial Basis Functions (FastRBF). RBFs are commonly used to approximate a method of kriging called Dual Kriging (Horowitz et al 1996). RBF is the creation of volume function as a sum of basis functions that use a linear weighting method in the same manner as dual kriging (Cowen et al, 2003). However, because it is a global interpolant it requires the entire dataset to be used when computing the weighting function. This can limit its application to smaller data volumes. The FastRBF operates in the same way as RBF, without the RBF requirement of infinite precision for the weighted calculation. Instead, input coefficients are only computed using a pre-determined accuracy, enabling rapid computation.

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Areas of interest (no known factual values) are estimated by interpolating and referencing nearby data points with known factual measurements using FastRBF. Each reference point has a weight-of-influence (factual measurement) that helps prioritize the estimation process. The function considers distance between the point of interest (point to be estimated) and weight of nearby reference points (factual values) and assumes reference points with higher weights of influence, that are nearer to the point of interest are more influential than points with less weight of influence or increased distance from the point of interest.

The rapid implicit ground modelling process (i.e., data driven) enabled timely updating and testing of the CGM, keeping the models dynamic and in synch with data acquisition and geological interpretation. As new data became available, continued updating and data review enhanced site characterization and geotechnical planning.

2.3 Visualisation of Stratigraphic & Geotechnical Data

During desktop study, three main soil units were classified:

1) Unit 1 - Recent undifferentiated alluvial and coastal deposits;
2) Unit 2 - Holocene-aged marine clay sediments; and
3) Unit 3 - Pleistocene to Holocene marine clays/coastal sands and alluvial gravels.

Point clouds were generated for the base depth of each soil unit and geotechnical properties including particle size distribution (PSD), moisture content and others (Figure 3). Digital surface trends were interpolated for each point cloud. For example, trends in SPT-N values were visualised in the manner shown in Figure 3 to define transitions from soft to stiff clays and loose to dense sands. When used collectively, these data helped to visualise relationships between soil type and geotechnical properties, allowing the interval points of the main soil units to be well informed and reviewed at an early stage. Trends and variations in the data, including anomalous or erroneous records were easy to isolate and interrogate in the 3D ground modelling environment for investigative follow-up.

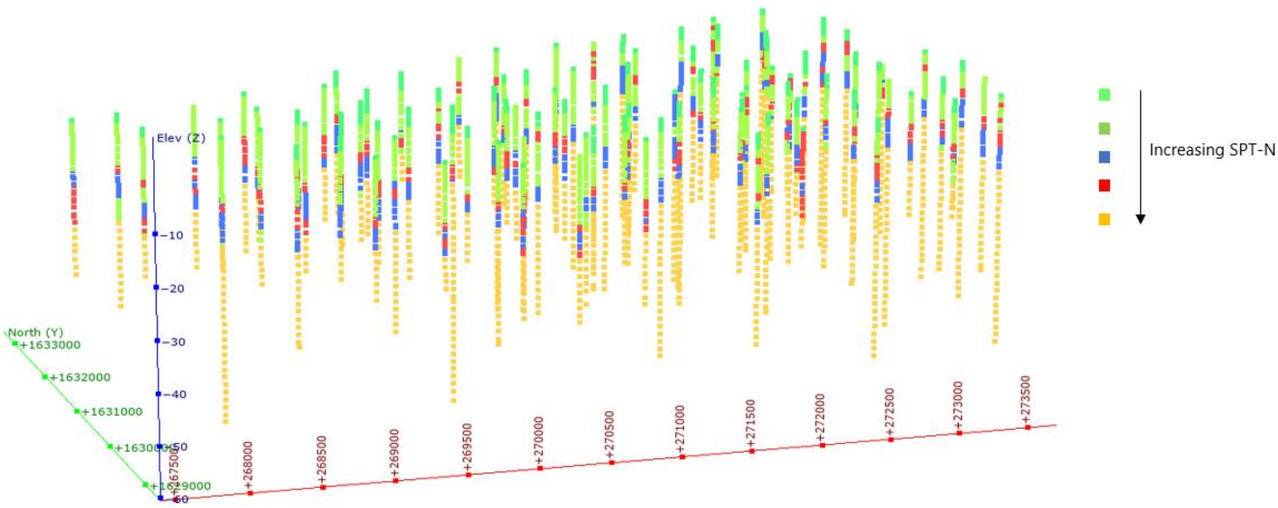

Figure 3: Point cloud for geological stratigraphy & geotechnical properties (SPT-N values, view northward)

2.4 Using the Ground Model to Inform Site Investigation

Block volumes for each soil unit were calculated using the interpolated digital surface trends. The thickness of finer sediments (Unit 2) increased with distance from the shoreline, and marine deposits with coarser sand and gravel sediments (Unit 3) were more abundant shoreward. The coastal and alluvial sediments often occurred as localized sheets and lenses of sand. The thickness of Unit 1 varied across the site and was generally dependent on the extent of anthropogenic disturbance. Based on the macro-scale evidence, the CGM was consistent with the pro-grading geomorphological setting, that had experienced cyclic sea level oscillations and changes in depositional environments.

The CGM evaluated predicted soil conditions for each proposed CPT location and reflects the findings from desk study and review of the general site stratigraphy. At each position, soil unit descriptive categories were extracted from the block volumes for the length of each CPT (Figure 4). A predictive log, including soil type, thickness, and expected geotechnical properties were derived for each location. This evaluation process ensured data acquisition was suitably scheduled and informed. When site constraints were encountered alternative CPT locations could be evaluated quickly, and intelligently screened to inform suitable CPT relocation, promptly and efficiently.

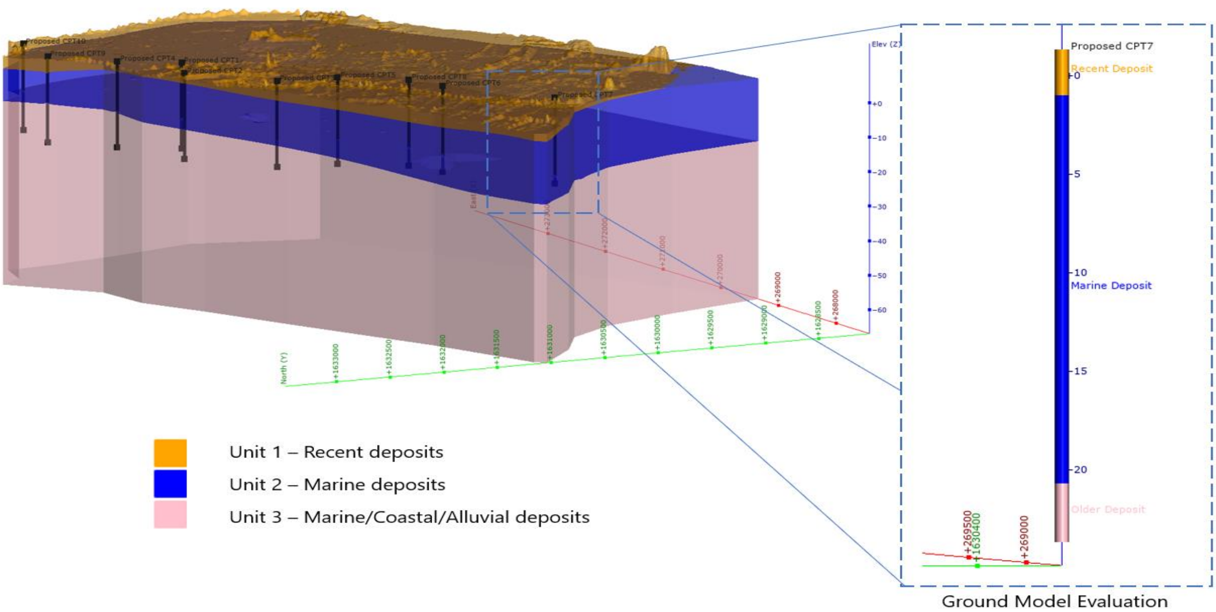

Figure 4: Using the conceptual Ground Model to evaluate stratigraphy at the location of Proposed CPT7 (view eastward).

3 Transition into an Observational Ground Model & Improving Data Acquisition

3.1 Using Implicit Modelling to Evaluate & Visualise Unique Soil Units

A key component of GRMF Stage **Δ**2 is digital transformation and integration of newly acquired CPT data with the existing CGM. The digitized cone resistance (q_c MPa), sleeve friction ratio (R_f %) and pore pressure (u kPa) numerical measurements were visualised and compared to soil behaviour type index (I_c, Robertson, 2010) qualitative measurements. CPT data measurements were cross-examined within the CGM block volumes. As shown in Figure 5, unique soil sequences, including lenses of shelly/silty sand mixtures were evident in the CPT I_c and q_c measurements.

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Two methods of interpolation were used to evaluate continuity and vertical and lateral variability of these unique soil sequences, namely Leapfrog Works Intrusion and Vein FastRBF.

The Intrusion FastRBF implicitly modelled ellipsoid 3D volumes of the shelly/silty sand mixtures. The depositional context (orientation of channels and delta plains, geological process), thickness of unique soil sequences and GI spacing were considered when assigning anisotropic input values for global trend and ellipsoid maximum, intermediate and minimum semiaxes. Ellipsoid output volumes were compared and checked visually with I_c and q_c stick logs (Figure 5) to explicitly refine these input values. The input parameters shown in Table 1 were deemed sufficient for the OGM derivatives. The final ellipsoid volumes highlighted continuity between the unique soil sequences across the site. However, gaps in the predictive data were evident (Figure 6a) and were likely associated with data density and measured thickness of these unique soil sequences.

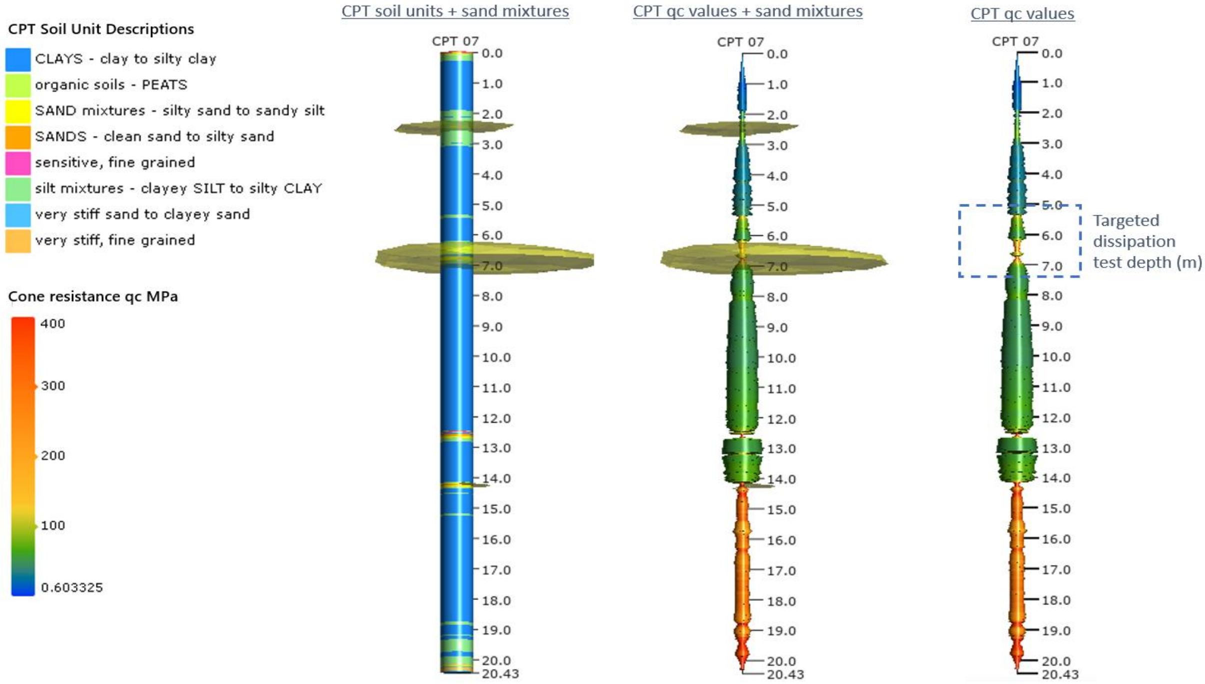

Figure 5: Comparison of sand mixtures ellipsoid volumes with I_c & q_c values of proposed CPT7.

Table 1. Compositing & trend parameters used to define model sand/shelly soil unit ellipsoid volumes.

Surface editing options	Ellipsoid Parameters	Input Values
Compositing	Filter interior	<0.2
	Filter exterior	<0.2
Trend	Dip°	0.2
	Azimuth	260
	Pitch	150
	Maximum ratio	500

	Intermediate ratio	250
	Minimum ratio	1
Model	Surface resolution	10.0

The Vein FastRBF models 3D volumes between two interpolant surfaces, that are computed from the upper and base depth values of each soil unit. The interpolant surfaces are extrapolated between each GI location with a measurement (i.e., the calculated surfaces must pass through each data point). A total 61 no. CPT locations, some 93.5% had recorded measurements of unique soil sequences. The Vein FastRBF produced output volumes with a continuous trend, inclusive of variable thickness for the unique soil sequences across the site (Figure 6b). The dip, azimuth, pitch, and surface resolution inputs of the global trend shown in Table 1 were used to inform the Vein FastRBF computations.

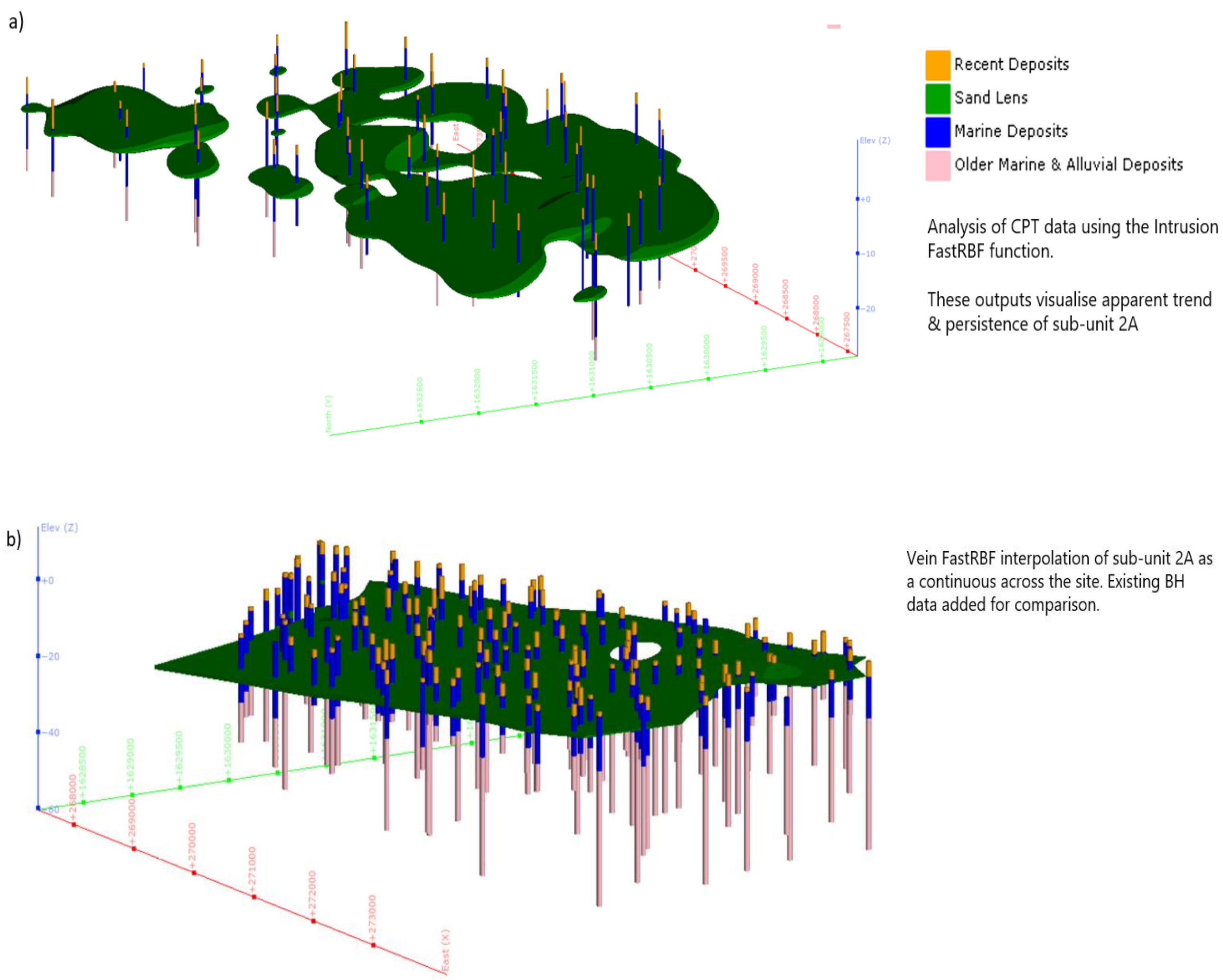

Figure 6a & 6b: Intrusion (a) & Vein (b) FastRBF output Volumes

The Intrusion and Vein FastRBF 3D volume outputs both highlighted some degree of continuity for the unique soil sequences across the site. However, the ellipsoid 3D volumes were not always continuous. As mentioned, gaps in the ellipsoid data were likely influenced by data density and/or measured total

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thickness of unique soil sequence measurements. Additional geospatial analysis was conducted to test these assumptions.

A kernel density spatial analysis was applied to calculate a magnitude-per-unit-area (in this case m^2) using all 61 no. of CPT locations. This generated heat maps that visualise the spatial density of these geographic data (blue in Figure 7). The darker the colour, the higher the data density per m^2.

A Natural Neighbour interpolation was conducted and used the measured thickness of unique soil sequences recorded in each CPT location. Contour plot trends were derived from the output rasters (Figure 7). The plan extent of the ellipsoid volumes was mapped against both the kernel density heat maps and the thickness of unique soil sequences contours. A correlation between CPT density and/or thickness of unique soil sequences to ellipsoid mapped extent was evident. In summary, the following patterns are apparent:

1) Areas with low density & low measured thickness have limited ellipsoid extents;
2) Areas with high density but low measured thickness have some, often localised ellipsoid extents;
3) Areas with low density but high measured thickness have some, often localised ellipsoid extents; and
4) Areas with high density and high measured thickness have greater, higher continuity ellipsoid extents.

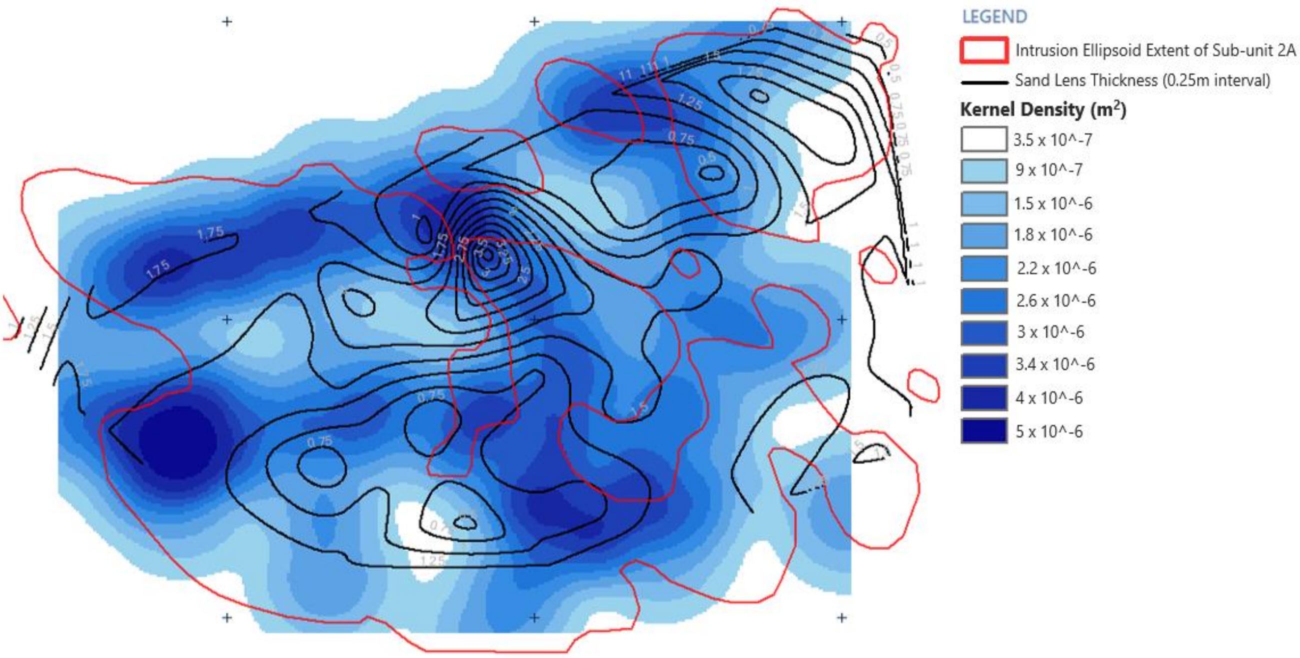

Figure 7: Comparison between ellipsoid extent, data density & unique soil thickness contours

The assessments supported the interpretation of a continuous unique soil sequence within the Holocene marine clays (Unit 2). It was classified as Sub-unit 2A and represented shelly/silty sand mixtures. After review of the geostatistical analyses and comparison of the Intrusion and Vein FastRBF output 3D volumes, the Vein FastRBF was considered most suitable to represent this Sub-unit within the OGM.

Updated predictive logs were evaluated from the OGM and used to further refine/inform the ground investigation expectations. When compared with preliminary factual logs these data added value by providing methods for review and conducting quality assurance and control of incoming data (Figure 8).

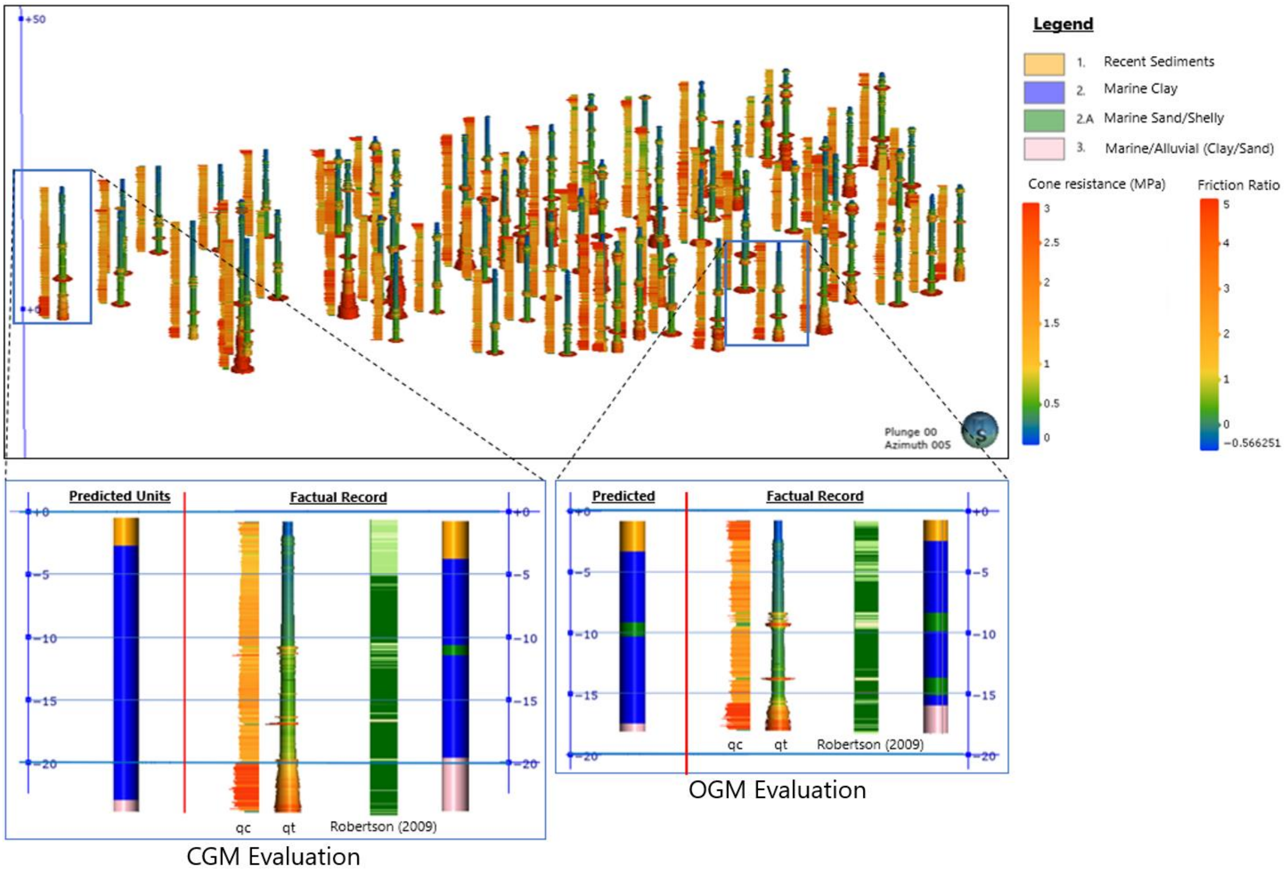

Figure 8: Visualisation of CPT data & comparison of predicted/factual records (left from CGM & right from OGM).

3.2 Improved Data Acquisition & Targeting Dissipation of Tests

The field team were informed about the expected soil properties discussed in Section 3.1 which assisted in their on-site review of the field test results and in making decisions for additional testing. The program allocation for the dissipation tests were aligned with the identified geotechnical units, with emphasis on establishing the hydraulic conductivity properties of the identified sand lens in the block model.

The geotechnical model assisted in the forecast of termination depths of the CPTs. As the execution of the program depended on the rise and fall of the tides, this led to better scheduling and allocation of resources during the geotechnical investigation. Early termination of CPTs to mitigate the risk of the CPT platform being stranded caused by the impending low tides was avoided in the program execution.

4 Geotechnical Zonation & Analysis

4.1 Using the Integrated Observational Model for Geotechnical Review

As described above, the integrated geotechnical model facilitates the visualization of the geospatial distribution of various sub-strata information, including soil properties and parameters derived from in-situ and lab testing. Data of interest can be visually graded or banded to establish the trends of material changes and their interrelation with the evolving ground model stratification, all contextualized within the geological and geomorphological site development history.

With the use of the 3D model, the relationship of proposed development layouts with underlying changes in the soil strata and the variation of soil properties affecting ground performance, such as strength and compressibility characteristics, can be fully appreciated by all stakeholders in the development of the project. Geotechnical project constraints and risks can more easily expressed and mitigation measures to manage such risks be taken into consideration early-on in the project life-cycle. Within the MIA project, the desktop study identified some areas of high moisture contents (Figure 9). With the model evolution, these high moisture content soils were observed to have a high lateral continuity beneath the base of the newly mapped Sub-unit 2A and were therefore distinguished from the upper soft clay Unit 2 as a further sub-unit, Sub-unit 2B. The soil properties and parameters, including the geomechanical properties affecting soil behaviour, were separately evaluated for Unit 2, Sub-unit 2A and Sub-unit 2B for subsequent analysis. The presence of the high moisture content layer tying in with the Sub-unit 2A layer of sandy/shelly/silty sand mixtures was contextualized within the site evolution as a cyclical change in the pro-grading depositional environment.

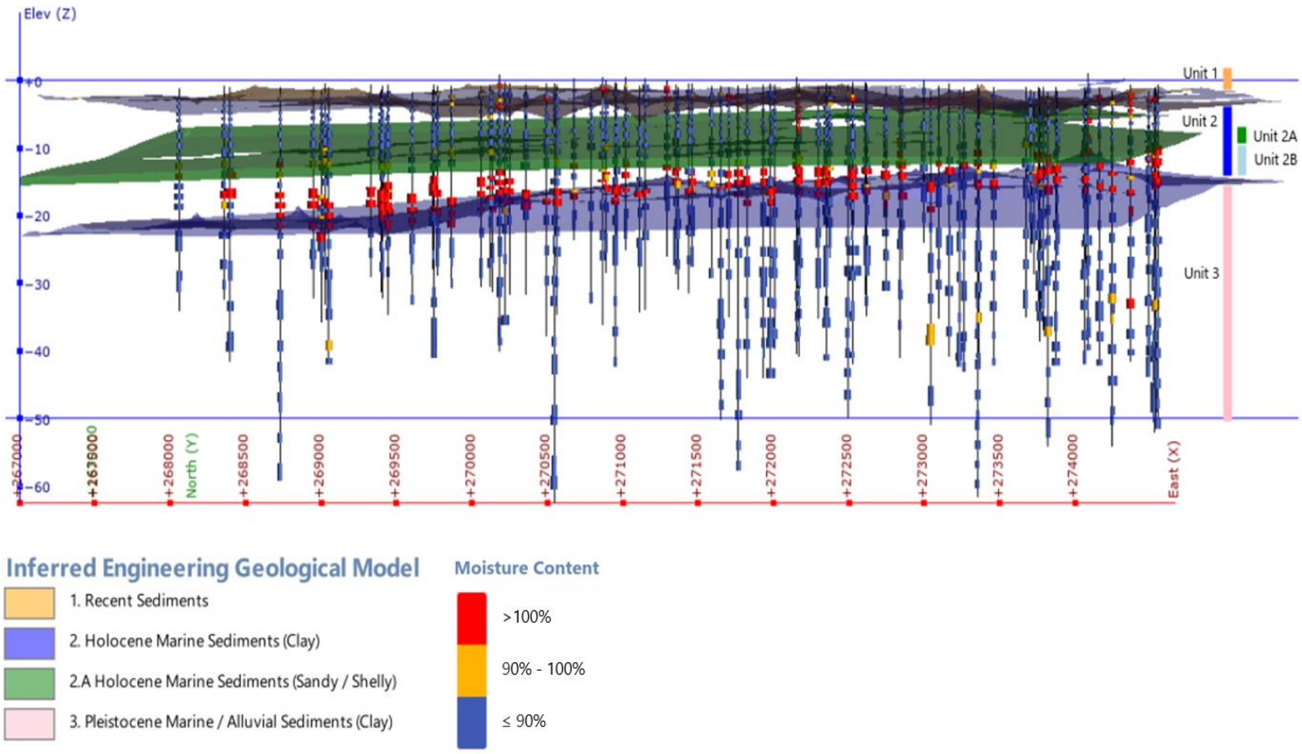

Figure 9: Comparing digital trends in soil moisture contents (view northward).

4.2 Zonation of the Site for Geotechnical Analysis

Within the context of any development project, geotechnical assessments can be provisionally undertaken on a generic basis, but more meaningful assessments generally need to consider the relationship between various elements of the development (such as different types of structures, loadings, foundations, and serviceability sensitivities) with variations in ground conditions upon which they are to be constructed. The facility zonation is generally derived from the development plot layouts in consultation with designers and project owners. Depending on the nature of the development and facilities, various factors of the ground performance will be of interest to designers and developers which will steer the geological/geotechnical zonation of the site in conjunction with the ground model. The scope of the required engineering assessments is subsequently based on the interrelation of facility and geological zonations.

In the case of the MIA project, the focus of the assessment was in relation to the site performance characteristics required for the new airport. Key issues under consideration were the compressibility of the soils, settlement magnitudes, consolidation durations as well as risk of liquefaction. Based on the modelled ground conditions, the site was split into 5 no. geological zones largely based on banded variations in thickness of highly compressible clay layers, the governing factor in settlement magnitude (Figure 10). Each of the 5 no. geological zones were examined in a 3D context to determine typical and worst-case profiles for settlement assessment with consideration to the filling zonation for the runways, aprons, and surrounding areas. An evaluation of the anticipated range of settlements over the site for consideration in the subsequent site formation and ground improvement design was carried out.

In reviewing consolidation settlements, both the magnitude and duration for settlements were of interest with the latter influenced by the drainage conditions at the site. In this context, the targeted data acquisition and dissipation testing during the CPT investigation campaign was able to aid the evaluation of the newly identified sandy/shelly layer Sub-unit 2A to act as a drainage layer. Further, in a localized corner of the site, the absence of Sub-unit 2A was also identified as a separate geological sub-zone where the duration for consolidation of the thick compressible soils without an intermediate drainage layer was most critical.

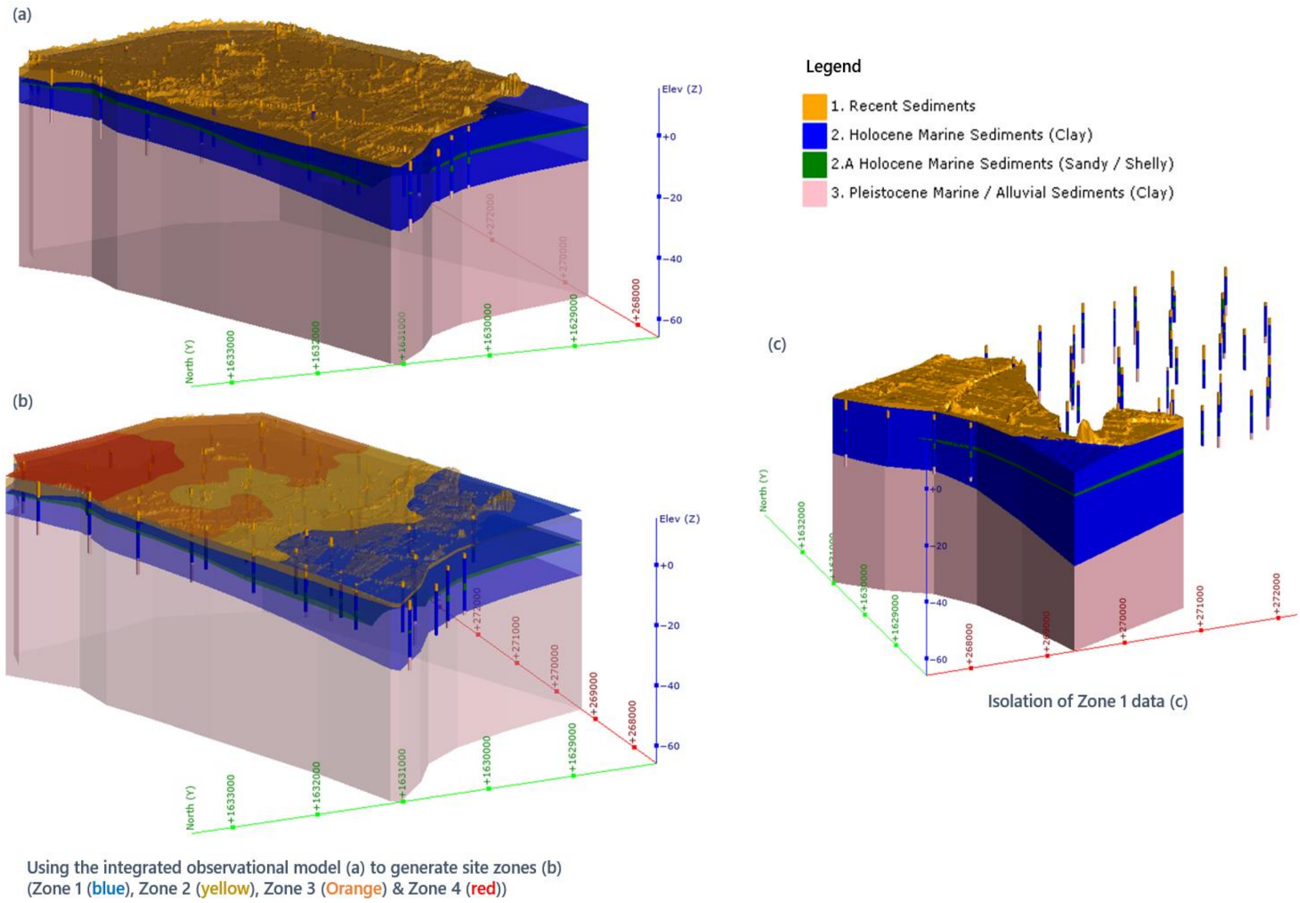

Figure 10: Using the Ground Model to generate geotechnical site zones (view eastward (a/b).

The findings of the settlement analysis showed that the settlement magnitude was not only affected by the overall thickness of the compressible layer but also the proportional thicknesses of the sub-units within the highly compressible layers that were identified through the geospatial modelling of soil property data. Where there was a greater proportion of the high moisture content layer Sub-unit 2B, greater magnitudes of settlements were anticipated resulting from the higher compression ratio of that sub-unit. Ultimately, the evaluation of settlement magnitudes across the development site allows for a preliminary estimate on the order of magnitude of top-up fill to attain the site formation profiling for consideration in the reclamation design. The distinction of the 2 no. soft clay layers above and below the sandy/shelly layer and the attribution of different parameter data would enable a more refined assessment of those magnitudes.

Furthermore, the refinement of the ground modelling that identified a laterally continuous sandy/shelly layer allowed for the consideration of a potential drainage layer within the thick, highly compressible clay layer. The effect of the refined drainage conditions reduced the time for 90% consolidation (t_{90}) between some 23 to 57 years. Whilst the reduction in t_{90} was significant and demonstrates the potential benefit of using an integrated observational model, the time for consolidation will ultimately be governed by the method of ground improvement adopted by future contractors.

5 Added-Value from the Ground Modelling Approach & Conclusions

5.1 Improved Planning of Site Investigations & Geotechnical Appraisal

For successful implementation of the ground modelling approach and to maximize project returns it must be adopted at the beginning of a project and used to set the precedence for future works. In this study, the ground model approach commenced during Stage $\mathbf{\Delta}^1$ of the Ground Risk Management Framework and was utilized through Stages $\mathbf{\Delta}^1$ and $\mathbf{\Delta}^2$. The purpose was to establish efficient project management, contract flexibility and clear communication of the understanding of ground conditions and ground investigation expectations.

Some key takeaways of the approach are that ground models combine implicit and explicit elements to allow geological knowledge to be tested, acquired, and validated more quickly, robustly and cost effectively. When used to interrogate data and inform ground investigation expectations digital models enhance focus and the targeting of high-quality data acquisition and geotechnical assessment. The ground model approach facilitates equitable and transparent sharing of ground knowledge and associated risks in geotechnical appraisal between all stakeholders. This leads to less conflict and easier project implementation.

For the proposed Manila International Airport (MIA), the ground model approach provided the following answers to the questions in Section 2.1:

1) The conceptual ground model constructed from existing information and desktop study data highlighted consistency with the known regional lithostratigraphy and soil sequences associated with a fluctuating deltaic geomorphological setting. The digital transformation and digital surface trend analysis of existing data was effective in predicting and enhancing ground investigation planning and expectations;
2) Using the implicit modelling elements of Leapfrog Works 4.0 (Seequent, 2020), newly acquired data were digitized and integrated seamlessly within the CGM framework. The 3D modelling

environment enhanced the methods of data interrogation; observations of unique soil unit sequences could be quickly tested, reviewed and patterns established. Through Stage Δ 2, the continued testing, comparison, and screening of new CPT data culminated in the identification of a soil Sub-Unit 2A. This encouraged further review of existing data, resulting in further refinement with the identification of an additional unique soil unit (high moisture content clays Unit 2B). The ground model approach allowed patterns and regional relationships to be carefully mapped, and correlations developed as more supporting data were acquired and eventually used to enhance the ground investigation and inform geotechnical assessment and zonation.

3) The use of the integrated observational model has allowed for refinement in the visualization and modelling of the ground conditions through targeted data acquisition during the CPT investigation campaign. In situ testing allowed for some understanding of the hydraulic and consolidation properties and more accurately classified the sub-soil units and their properties for subsequent geological zonation and engineering assessments. These refinements facilitate a more representative assessment on the potential settlement implications of the fill materials for consideration in detailed design. Based on the specific parameters of the sub-units, the compression ratio of the high moisture soft clay layer was approximately 20% higher than mean compression ratio over the whole of the highly compressible stratum. Without being modelled, this would have led to an underestimation in the expected magnitudes of consolidation settlement particularly in those areas where the proportion of the high moisture content sub-unit is greater. It was also observed that in general the proportion of prior sampling and geomechanical testing of the high moisture content sub-unit was relatively limited and targeting this layer for some additional data validation in the subsequent design and build stage has been advised.

Spatial variability in the ground model data can be reduced by continued management and integration of new data throughout the project lifespan This initial MIA ground model was a first-step benchmark to visualize the site conditions for GRMF Stage $\mathbf{\Delta}^1$ and $\mathbf{\Delta}^2$. As GRMF Stage $\mathbf{\Delta}^3$ commences, and beyond, new geotechnical data, instrumentation monitoring, and construction feedback should be used to refine the assumptions of the evolving ground model to improve its quality and representativeness. This will enhance its capacity to support analytics, design, and open opportunities for integration with Building Information Modelling (BIM) as a supplementary toolkit providing advice and recommendations to project stakeholders.

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