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Review of the importance of detailed sample inspection for input to the ground model and geohazard assessment

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ABSTRACT: Detailed sample inspection, observation and integration are critical to improving the understanding of geotechnical test results, the evolving geological model and geohazard assessment. However, variability exists between developers in how much time and costs of the overall project is dedicated to detailed sample inspection. It is often dependent on the availability of samples and the understanding of the geological history of the site and is not performed as standard despite the relatively low cost and time implications to the overall project and the increased knowledge that can be developed from the detailed inspection in the site characterization.

This paper presents learnings from a global project example highlighting the importance of making observations on individual samples through geologically focussed hand specimen description, detailed sedimentological logging and microscopic analysis to ensure a comprehensive understanding of composition and structure for input into the geohazard assessment and particularly slope stability analysis.

The project is in a complex geological location where it was deemed important to understand the evolution of the sediments to aid data integration, ground modelling and geohazard assessment. An initial desk study was compiled including recommendations for targeting detailed geological logging.

The advice that samples should be inspected on the macro- and microscale, with observations integrated into the developing ground model, ensured a comprehensive understanding of the evolutionary history of the site; which combined with the site-specific input into the geohazard assessment within the time frame of the site investigation meant there was therefore minimal impact on the overall project timeline.

Keywords: Geological logging, slope stability assessment; evolutionary history; integration

1 INTRODUCTION

A slope stability assessment requires a detailed understanding of the soil conditions to ensure the inputs to the assessment are appropriate and constrained (Madhusudhan et al., 2017; Mackenzie et al., 2010). These inputs, including unit weight and undrained shear strength can be obtained from a standard geotechnical site investigation with associated laboratory testing. However, the geotechnical testing will be performed on the bulk unit and focusses on ensuring parameters can be derived for detailed design of foundations for infrastructure. For input to the ground model and geohazard assessment it is beneficial to integrate sedimentological logging with the assignment of geotechnical testing as well as the final geotechnical results to ensure the inputs are appropriate for the analysis being performed.

This paper highlights the value of acquiring geological specific samples during a planned geotechnical site investigation to ensure comprehensive understanding of the ground conditions for input into site-specific geohazard assessment and how assigning sedimentological logging was fed back into the ground model to fully characterise the sediments and their evolutionary history. In addition, the sedimentological logging ensured the geotechnical testing was appropriate and performed on specific sediments relevant to the slope stability and therefore the wider geohazard assessment.

2 PROJECT AND GEOLOGICAL SETTING

The development is located at the base of a slope in water depths of more than 1000 m and is connected by a pipeline route up the slope onto a shelf. The seafloor morphology is generally flat and featureless although there are isolated areas of undulating topography at seafloor which are the result of basin floor fans at or near surface. Slope gradients of the seafloor generally range between 0° and 2°, although slope angles up to 5° were also calculated where bedforms are present at surface.

Depositional and post-depositional processes in the region were controlled by sea level variations related to transitions between glacial and interglacial periods. During the early Pleistocene a prograding sediment wedge formed during lowstand periods. Subsequent fluctuations in climatic conditions led to the extensive erosion and redeposition of sediments in the region.

During glacial periods in the Pleistocene an ice sheet was grounded on the shelf and sea levels were significantly lower than present day. Sediment accumulation on the slope and in the channel occurred in a glaciomarine setting; however, periodic mass failure of sediment occurred directly from the ice sheet deposited on the slope. Post depositional erosion and redeposition of the sediments by bottom currents was also evidenced. The result of the complex interaction between these processes led to the deposition of the predominately clay profile interspersed with laminations and beds of silt and sand.

3 DESK STUDY

A desk study was completed for the development area to provide geological context, definition of the stratigraphy based on geological setting, seismostratigraphy and previous data acquisition campaigns; a geotechnical zonation of the development area and a 1D slope stability assessment performed using an infinite slope geomechanical model for both static conditions and under pseudostatic conditions. The desk study concluded that based on the available information the slopes were shown to be stable under static and pseudostatic conditions using the 1D model; however, limitations in the understanding of the geotechnical properties remained, particularly in relation to characterising sand and silt laminations within the predominantly clay profile and how these contribute to the confidence around the potential for slope instability. The AFEN failure (named after the Atlantic Frontier Environmental Network who mapped it) situated on the West of Shetland slope, for example, is hypothesised to have occurred as the result of liquifaction of sand and silt laminations as a result of an external trigger (Madhusudhan et al. 2017) and thus the nature of any sand being present in the profile was important to understand further and fully characterise. At this stage it was therefore recommended that additional geotechnical data were required to ensure the sediments were fully characterised.

During a planned geotechnical site investigation, piezocone penetration tests (PCPT), gravity cores (GC), piston cores (PC) and boreholes (BH) were sited to acquire geotechnical data for input to the overall site characterisation of the development area. The results of the desk study were utilised to define two locations on the slope where PCPT and borehole samples were acquired and geological logging was recommended to further characterise the sediments for input into the geohazard assessment including slope stability assessment. These proposed boreholes added minimal additional data acquisition costs as the boreholes were added into a planned acquisition programme.

The two geological specific locations are located approximately 13 km apart on the slope and are summarised in Table 1.

Table 1. Locations acquired for sedimentological logging

Location No.	Approx. Water Depth [m]	Target Depth [m]	Recovery [m]
1	800	20.0	21.25
2	580	20.0	20.80

The locations were paired seabed PCPTs and downhole borehole sampling. The samples were saved in the liners, but geotechnical testing including pocket penetrometer, torvane, unit weight and moisture content was performed on the top and bottom of each liner to contribute to the unit characterisation.

Following the site investigation, multiple geotechnical units were identified which were correlated with the geophysical interpretations. The transitions between the geotechnical units reflected relatively subtle changes in lithology and geotechnical characteristics, and particularly in frequency of sand and silt laminations, and the identifaction of these unit transitions on the geophysical data was limited. Thus there was uncertainty in correlating the identified units away from the geotechnical location.

4 DETAILED SEDIMENTOLOGICAL LOGGING

Hand specimen descriptions for geotechnical purposes are performed offshore and in conjunction with laboratory testing; however, there are instances where closer inspection and detailed delineation of the frequency and composition of laminations is important particularly in the understanding of the geohazard assessment for the site.

The site-specific PCPT results indicated normally consolidated clay; however, peaks in cone resistance were present which were attributed to either pockets, laminations or beds of sand or a single gravel or cobble on the field logs; however, further detail on the composition and continuity were required in order to fully characterise the unit for input to geohazard assessment. This was where detailed sedimentological logging coupled with microscopic observations proved very informative for understanding the composition, extent and continuity along the slope of the coarse material inclusions.

The samples acquired offshore were kept in liners and capped with minimal geotechnical testing performed offshore. In the laboratory, the samples were cut vertically in the liners and the sample split to create a clean surface on which to identify the key features. A high-resolution photograph of the split liner surface was taken. The samples were described in alignment with the British Standard (BSI, 2018) and included additional information that was pertinent to the understanding of the geological processes. A graphical log was drawn of the sample to detail depositional and post-depositional features, bedding and erosional surfaces and the nature of bedding contacts (Figures 1 and 2).

The geotechnical description available from both locations performed offshore indicated the samples generally comprised extremely low strength to medium strength sandy CLAY with laminations of sand. Figure 1 illustrates some of the key features identified at Location 1 where it was apparent that the laminations of sand interpreted from the geological setting, identified from the CPT and summarised in the geotechnical description performed offshore was more complex. The detailed descriptions highlighted three main occurrences of sand within the borehole:

- Laminations of medium sand coarsening up to coarse sand;
- Thick laminations of very clayey sand to sandy clay;
- Pockets of clayey sand to sandy clay.

In addition, it was observed that there was significant lateral variability in the sediments highlighted by the poor correlation between the observations from the logging and the seabed PCPT location which were generally within 5 m lateral distance of each other.

Figure 2 highlights the main features observed in Location 2 where the amount of sand observed was generally greater than in Location 1. The sand was constrained to thick laminations to thick beds below 5 m BSF. Where the thicker sand beds were observed these were characterised by both normal and reverse grading.

The detailed sedimentological logging also highlighted the peaks identified within the PCPT data are the result of a combination of beds of sand, laminations of sand, pockets of sand, gravel and cobbles within the profile.

To support the geologist's observations during the sedimentological logging, the sediments were also locally reviewed at the micro scale. This highlighted that the sand fraction generally comprised quartz, lithic fragments comprising gneiss, granite and slate and bioclastic debris which gives an indication to the origin of the sediments further supporting the developing evolutionary model.

The detailed sedimentological logging also facilitates a detailed review of the fabric of the clay unit. Although in the case of this project the clay units were generally massive, local changes in fabric of the clay units can affect geotechnical test results and therefore can be an important output of the sedimentological logging to fully characterise the soils.

The results of the detailed sedimentological logging were used to inform the laboratory testing programme and sub-sample selection, in particular, the identification of the thicknesses of sand suitable for subsampling for site-specific shearbox and isotropically consolidated drained triaxial testing, therefore only the clean sand beds were tested, minimising inclusion of cohesive material in the sample for the testing. This ensured that a more representative angle of internal friction could be determined for the sand sediments on the slope, an important input into the slope stability assessment and engineering design.

5 IMPLICATIONS FOR THE GROUND MODEL

The use of detailed sedimentological logging on site-specific dedicated samples highlighted a number of key features which were fed back into the ground model and the geohazard assessment to support the site characterisation.

The understanding of the nature of the beds of sand were used to update the geological setting for the site. The presence of variable grading profiles within the beds of sand highlighted that different depositional processes had been active at the site. At the desk study stage it had been identified that deposition directly from the grounded ice sheet had occurred; however, from the result of the logging it was interpreted that the sediments were deposited from both mass transport processes and also contourite activity at the site. Although this was identified as feasible based on the regional data, no site-specific information was available to confirm the composition or distribution relative to the proposed development.

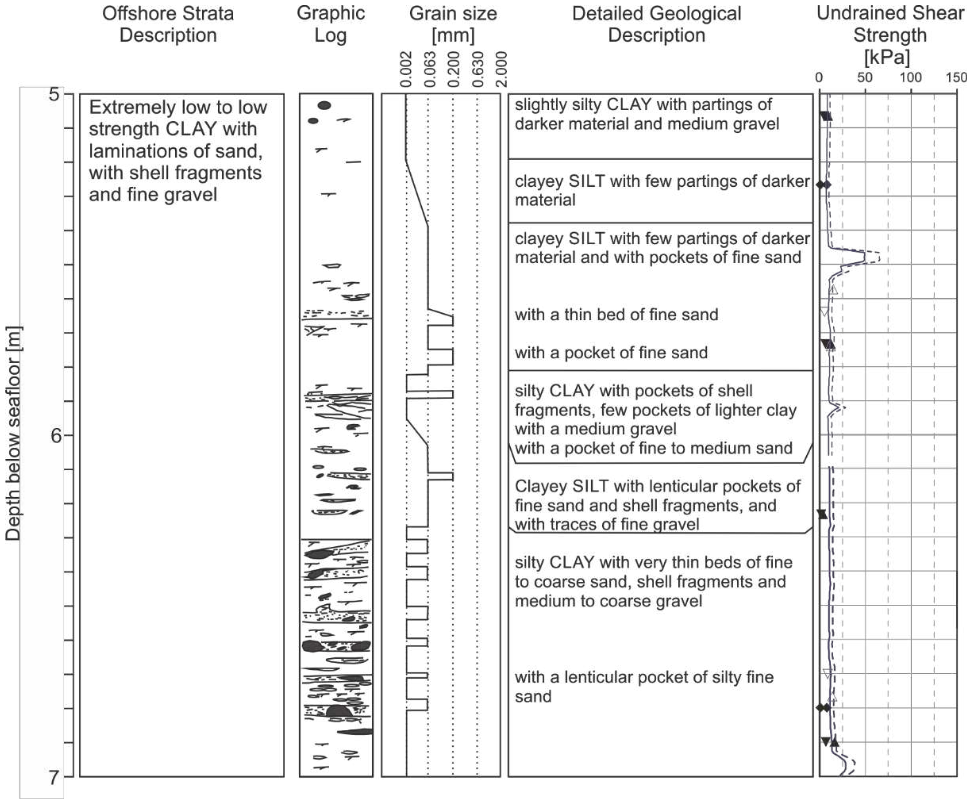

Figure 1. Illustrative example of offshore strata description and added detail from the detailed sedimentological logging at Location 1. Undrained shear strength as defined from CPT determined using an N_{kt} value of 15 (dashed line) and 20 (solid line). Triangles represent undrained shear strength determined from pocket penetrometer and torvane tests

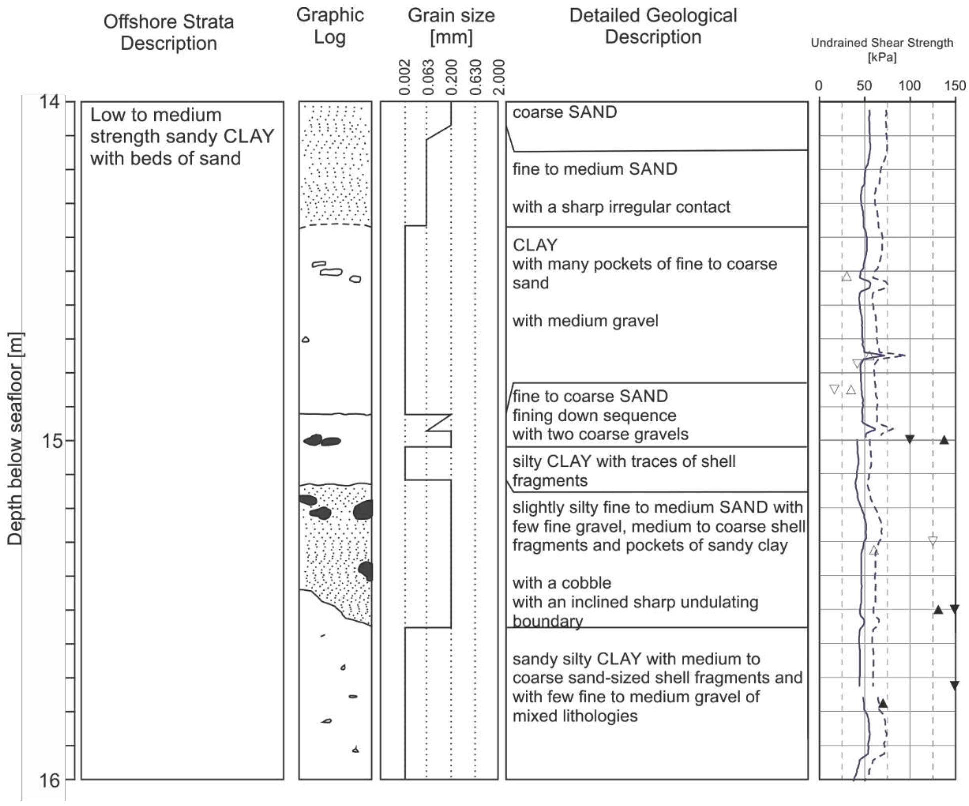

Figure 2. Illustrative example of offshore strata description and added detail from the detailed sedimentological logging at Location 2. . Undrained shear strength as defined from CPT determined using an N_{kt} value of 15 (dashed line) and 20 (solid line). Triangles represent undrained shear strength determined from pocket penetrometer and torvane tests

The integration of the findings also highlighted the potential for variability over relatively short distances within the area as highlighted by the offset in depths of identified conditions between the CPT and BH location.

The 1D slope stability analysis performed at the desk study stage highlighted the slopes had a factor of safety of more than 2 for the conditions inferred to be present based on regional data. Uncertainties remained when considering the regional data alone that needed to be investigated further in order to ensure confidence in the input data and therefore the conclusions of the slope stability assessment. The sedimentological logging highlighted the variability over short horizontal and vertical distances which was not identified from the regional data. Further, the logging provided targeting of the site-specific geotechnical data which ensured only the sand was tested using shear box and CID ensuring the input values to the slope stability assessment were valid and appropriate. Following a reperformance of the slope stability assessment, the slopes based on the updated input information were still shown to be stable based on the 1D analyses model.

In addition to the update to the slope stability assessment, the findings of the detailed sedimentological logging were utilised to update the geohazard inventory for the project. The interpretation of the different depositional processes were also fed into the understanding of the evolutionary model. Therefore ensuring the ground model was fully updated to include the findings of the geotechnical site investigation including the integration of geotechnical, geophysical and geological interpretations.

6 CONCLUSIONS

A project example is presented which highlights the importance of looking at the sediments on the millimetre scale through sedimentological logging to identify features for input to the ground model, targeted geotechnical testing and the geohazard assessment.

The scale of the use of detailed sample inspection needs to be considered within the overall project and will be dependent on what geological and geotechnical hazards and constraints are identified at the desk study stage or from site-specific geophysical interpretation. Once the hazard or constraint is identified an inspection plan can be created.

This example highlights a project where the dedicated boreholes and samples were acquired to provide detailed understanding of the site conditions; however, other projects are more reactive with only spare geotechnical wax samples utilised for the descriptions. This reactive approach can lead to key features being missed or geotechnical testing being performed on inappropriate samples. Detailed observations and descriptions cannot replace any quantified result; however, it is a relatively efficient and low-cost approach and is an important step in the understanding of depositional and post-depositional processes of the sampled and tested sediments. It is the authors recommendation that a geological specific core or sampling borehole is considered where specific geological processes identified at the desk study stage need further investigation. Through detailed planning with the ground model these can be acquired with minimal impact on the site investigation programme, but the return on ensuring better understanding of the site conditions can be large.

AUTHOR CONTRIBUTION STATEMENT

Lorraine O'Leary: Conceptualisation, Formal Analysis, Investigation, Writing- Original draft. **Vithiea Peang**.: Validation, Supervision.

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