Geotechnical site investigation challenges in extremely soft marine clays: a Baltic Sea case study

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Abstract. Offshore geotechnical site investigations in the Baltic Sea are often challenged by complex depositional environments and the presence of soft Holocene sediments overlaying glacial deposits. This paper presents the experience from a site investigation campaign carried out in the Baltic Sea, with the objective of characterising an offshore wind farm export cable route through a combination of cone penetration testing and vibrocoring, supported by a preceding geophysical survey. The geophysical interpretation indicated the widespread presence of marine deposits overlying glacial till. The main operational challenge arose from the integrated seabed rig, which proved unstable under the extremely soft seabed conditions. Mitigation measures included the deployment of piston cores and an independent cone penetration testing unit, which allowed data collection but limited penetration capability into the underlying glacial till. Despite an extended campaign duration, the geotechnical investigation successfully achieved its objectives. In-situ and laboratory testing revealed extremely low-strength clays with high to very high plasticity at the mudline, with undrained shear strengths typically below 10 kPa within the upper four metres. The findings underline the importance of flexible site investigation strategies and adaptive equipment selection when dealing with soft marine clays in glaciated seabed environments.

1 Introduction

The development of an offshore wind farm (OWF) requires comprehensive data acquisition and interpretation to support the planning, design, and installation of physical infrastructure, including foundations, export and inter-array cables, and other offshore elements. The required data are obtained through desk studies, geophysical surveys, and geotechnical site investigations carried out within the lease area and along proposed cable routes, well in advance of construction. The primary objective of this site investigation was to mitigate geological risk. This is to be achieved by using the obtained data to inform appropriate construction methodologies and ensuring the integrity of foundation and cable systems.

Offshore survey fieldwork in the Baltic Sea and adjacent basins is often challenging due to a complex depositional environment, shaped by multiple advances and retreats of ice sheets during successive glaciation periods, followed by the accumulation of marine and lacustrine sediments. This geological history has resulted in a highly variable stratigraphy, in which glacial deposits and erosional surfaces are frequently overlain by soft Holocene sediments at the mudline.

A case study from a reconnaissance site investigation campaign is presented, with the objective of characterising an offshore export cable route corridor where unexpectedly extremely low-strength clays were encountered at the mudline. Operational challenges faced during the fieldwork are highlighted, with the mitigation measures implemented to successfully complete the campaign, resulting in limitations for the acquired dataset. A brief characterisation of the soft clays in the study area is also provided, to establish a geotechnical basis for the lessons learned.

2 Geological setting and geophysical results

A sound understanding of the geological setting of the study area is essential prior to the execution of any geotechnical site investigation. This is usually achieved through geological desk studies and reconnaissance geophysical surveys, undertaken during the early stages of project development.

This section presents the geological context relevant to the investigation, summarising the outcomes of the geophysical survey, including the methods adopted.

2.1 Geological context

The geological context of the study area is characterised by Holocene and postglacial sediments overlying glacial till deposits. The Holocene units are predominantly comprised of marine clays, whilst postglacial sediments include variable fine-grained and granular materials associated with marine and transitional depositional

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environments. Beneath these units, the glacial till forms a regionally extensive foundation layer [1,2].

The glacial till comprises a heterogeneous, poorly sorted matrix of clay, silt, sand and gravel, deposited during successive phases of glacial advance and retreat. As a result of its glacial origin, the till typically exhibits high stiffness and density, with pronounced variability in composition and engineering properties. The repeated glaciations that affected the Baltic region have played a key role in shaping the present-day stratigraphy [3,4], resulting in strong vertical and lateral contrasts between soft Holocene deposits and underlying glacial materials.

2.2 Geophysical survey and interpretation

A geophysical survey was conducted to characterise seabed and shallow sub-seabed conditions and to support export cable route planning. The survey comprised multibeam echosounder (MBES), side-scan sonar (SSS), sub-bottom profiler (SBP) and magnetometer acquisition. Survey line spacing varied from approximately 15 m in nearshore areas to up to 35 m offshore, reflecting changes in water depth and survey objectives.

Sub-bottom profiling was carried out using an Innomar SES-2000 parametric system, operating at a central frequency of 8 kHz in a single-pulse configuration. Before being interpreted, raw SEGY data were processed by following standard workflows, including noise attenuation and frequency filtering. Interpretation of SBP data focused on approximately the uppermost 5 m below the seabed, corresponding to the depth interval most relevant to cable burial assessments and route optimisation.

Water depths along the export cable corridor reach up to approximately 62 m. Seabed morphology derived from MBES and SSS data indicates widespread trawl-induced seabed scarring across large portions of the corridor, together with discrete areas of higher acoustic backscatter associated with harder substrates, locally including boulder fields.

Interpretation of SBP data identified a three-unit stratigraphic framework, as illustrated by the representative example shown in Fig 1. The uppermost unit comprises surficial sediments that are largely seismically transparent to weakly reflective, with occasional low-amplitude internal reflections and isolated hyperbolic features attributed to buried point reflectors, most likely individual boulders.

Underlying this unit, a second stratigraphic unit is characterised by laterally continuous, sub-parallel reflectors of low to intermediate amplitude. The boundary between the uppermost and intermediate units is conformable, indicating continuous sedimentation, without evidence of significant erosion or interruption.

The lowermost unit identified in the SBP data is distinguished by a strong, high-amplitude upper reflector and the absence of resolvable internal structure. The boundary with the overlying unit is marked by a clear unconformity, indicative of an erosional surface formed prior to the deposition of the overlying sediments. This basal unit locally outcrops at the seabed surface and is associated in MBES and SSS datasets, with areas of high backscatter corresponding to cobble- and boulder-rich seabed conditions.

Based on the integrated interpretation of SBP, MBES and SSS data, the basal unit is interpreted as glacial deposits, while the overlying conformable units are interpreted as post-glacial to Holocene marine sediments, infilling the pre-existing glacial topography. This interpretation is consistent with the anticipated regional geological setting, described in Section 2.1, confirming the conceptual geological model of the study area. This stratigraphic framework provided the basis for planning and executing subsequent investigations.

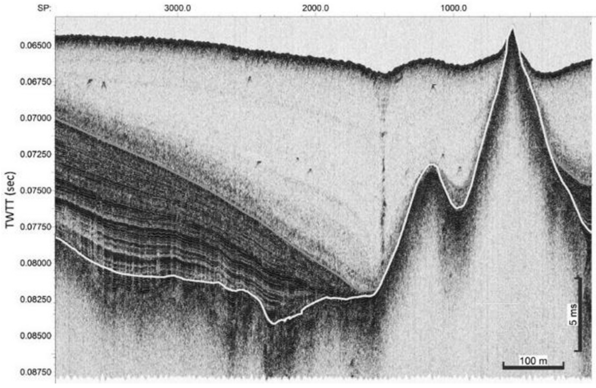

Fig 1. SBP profile with interpreted stratigraphic horizons.

3 Geotechnical site investigation

This section describes the scope of work for the geotechnical site investigation alongside the operational challenges faced during offshore execution and the mitigation measures implemented to successfully complete the campaign. The data limitations associated with the adopted mitigations are then discussed.

3.1 Geotechnical scope of work

The preceding geophysical survey indicates that Holocene and postglacial sediments are distributed widely across the development area. However, the internal consistency, composition, and geotechnical behaviour of these units remained insufficiently understood. To address these uncertainties, an initial geotechnical site investigation programme was developed comprising vibrocore (VC) sampling and co-located shallow cone penetration tests (CPT) along the cable route, executed in accordance with the requirements of ISO 19901-8 [5].

Shallow sampling along the cable corridors was planned, with a target penetration depth approximately 6 m below seabed. The objective was to characterise near-surface stratigraphy and recover representative material for engineering assessment. These sampling activities were complemented by co-located shallow CPTs to provide continuous profiles of mechanical response and to further delineate stratigraphic variability relevant to cable design and installation.

All of the samples recovered were subjected to a comprehensive geotechnical laboratory test programme. The laboratory data provided detailed material classification, alongside strength characterisation, forming the basis for the derivation of engineering parameters used in subsequent design assessments.

3.2 Operational challenges

The geotechnical site investigation was initially designed around an integrated seabed system, combining shallow CPT and vibrocore capabilities to allow co-located in-situ testing and sampling to be performed from a single deployment. This approach was selected to streamline offshore operations, reducing the number of seabed landings, and minimising operational and health and safety risks associated with repeated equipment handling and positioning. Under typical offshore conditions, such an integrated system offers clear advantages in terms of efficiency, data alignment and overall risk mitigation.

However, the shallow CPT and VC campaign encountered significant operational challenges, largely attributable to the extremely soft seabed conditions encountered across the survey area. The combined CPT–VC system, characterised by an inherently top-heavy configuration, proved unsuitable for the prevailing ground conditions. Upon seabed contact, the system frequently experienced excessive penetration, loss of verticality and subsequent tipping of the seabed frame. These issues resulted in repeated unsuccessful landing attempts, requiring frequent recovery of the equipment and leading to substantial interruptions to offshore operations. As a result, only a single investigation location could be successfully completed using the integrated system. An example of CPT response under these conditions is shown in Fig 2, highlighting low cone resistance and predominantly undrained behaviour of the shallow marine clays, with pore pressure ratios typically exceeding 0.5. These characteristics are indicative of extremely low shear strength and limited bearing capacity at seabed level, which directly explain the instability and poor landing performance of the seabed systems.

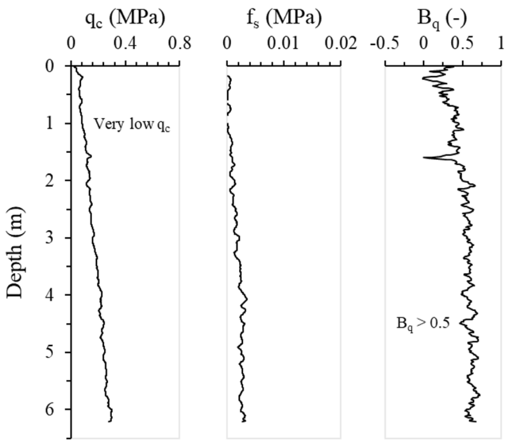

Fig 2. CPT profile from a selected location along the corridor, showing cone resistance (q_c), sleeve friction (f_s) and pore pressure ratio (B_q).

Similar challenges were encountered during the deep-scope investigation within the wind farm area, where the same very soft seabed conditions persisted. The continuous-drive CPT system, originally configured with a seabed frame capable of delivering up to 20 tonnes of thrust, also experienced excessive sinkage upon landing. To mitigate instability and allow testing to proceed, the ballast plate was removed to reduce the overall system weight. While this modification improved landing stability, it required the available thrust capacity to be reduced by approximately half, thereby limiting the operational capability of the system during the subsequent testing programme.

Collectively, these observations highlight the inherent difficulties associated with deploying heavy or top-heavy seabed systems in environments characterised by very soft marine sediments and extremely low undrained shear strength.

3.3 Mitigation measures and data limitations

In response to the operational difficulties encountered under extremely soft seabed conditions, a series of targeted mitigation measures were implemented to maintain operational safety and allow the geotechnical site investigation to progress. The instability issues observed during equipment deployment highlighted limitations in the initial equipment selection, which had not fully accounted for the very low bearing capacity of the near-surface sediments. The limited availability of pre-survey geotechnical data further contributed to an underestimation of the undrained shear strength of the upper soil layers, necessitating adjustments to both the equipment and the investigation approach.

A key mitigation measure involved replacing the integrated CPT–VC system with separate, dedicated systems. This change enabled the deployment of an independent, lighter and more centrally balanced CPT system, together with a stand-alone piston corer (PC). The separation of sampling and in-situ testing significantly improved landing stability and operational control, effectively eliminating the instability issues associated with the top-heavy integrated configuration.

For sediment sampling, an independent gravity piston corer was adopted to achieve controlled penetration and minimise sample disturbance in soft Holocene marine sediments. However, this approach introduced an inherent limitation: the piston corer was unable to penetrate the underlying glacial till. At locations where the till surface occurred shallower than the target penetration depth of approximately 6 m, sampling had to be terminated prematurely. Consequently, full-depth sampling could not be achieved at all locations, resulting in localised gaps in the near-surface stratigraphic dataset; however, these gaps are indicative of the presence of stiffer underlying materials, which, while not directly sampled, were identifiable at a stratigraphic level through integration with geophysical data.

Finally, the revised equipment configuration did not allow for the acquisition of in-situ thermal conductivity measurements. Thermal properties were therefore derived exclusively from laboratory testing on recovered samples. As no in-situ thermal measurements were available within the same soil units, the laboratory-derived values could not be directly validated against field data, representing a further limitation of the revised investigation approach.

Despite these constraints, the implemented mitigation measures provided a robust and adaptive response to the operational challenges associated with extremely soft marine sediments and locally shallow glacial till. The revised investigation approach enabled CPT acquisition and sediment sampling to be completed along the cable routes to a level sufficient to support the development of a reliable Geotechnical Interpretative Report (GIR) for cable design.

4 Soft marine clays characterisation

This section presents the geotechnical characterisation of the soft marine clays identified along the corridor.

Providing a concise description of their index properties and undrained shear strength is considered essential, as these parameters largely explain the operational difficulties encountered during the geotechnical site investigation. By outlining the key features of these sediments, this section also helps define the soil conditions under which similar challenges may arise in future offshore investigations.

4.1 Soil behaviour type

A preliminary classification of the clays identified along the corridor was carried out through interpretation of the raw CPT data acquired during field testing. While CPT measurements do not provide a direct identification of soil type based on physical properties, they offer valuable insight into the mechanical response of the soil, commonly referred to as the soil behaviour type.

Representative CPT data illustrating the conditions encountered along the corridor are presented in Fig *2*. As both cone resistance and sleeve friction increase with depth due to the increase in effective overburden stress, CPT data require normalisation to account for stress effects, particularly for very shallow investigations. One of the most widely adopted soil behaviour type charts based on normalised CPT is that proposed by Robertson [6]. This chart identifies general trends in soil response, such as stress history, sensitivity and organic content in cohesive soils, based on the combined interpretation of normalised cone resistance Q_{tn} and normalised friction ratio F_r.

An example of this interpretation is shown in Fig 3, where the Robertson soil behaviour type chart for a selected location along the corridor is presented. The data points consistently plot within the "clays" domain, falling predominantly within the zone associated with young, normally consolidated soils. A slight tendency towards the "sensitive fine-grained soils" is observed, while no indication of organic soils is evident. This behaviour is representative of the CPT response observed along the entire corridor, allowing the identified deposits to be classified as normally consolidated clays with low to moderate sensitivity.

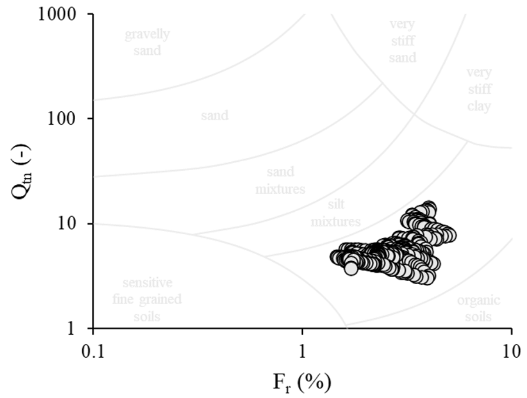

Fig 3. Robertson soil behaviour type chart for a selected location along the corridor.

4.2 Particle size distribution

The soil classification inferred from CPT measurements was complemented and verified through laboratory-based classification testing. Fig 4 presents the particle size distribution (PSD) curves of the clay deposits identified along the investigated corridor. PSD data were used to quantify the relative proportions of clay, silt and sand within the sediments. Soil classification based on particle size follows the boundary limits defined in the relevant ISO standard [7].

The results confirm that the investigated deposits are fine-grained, with an average sand content (particle size $>$ 0.063 mm) of approximately 4.5%. Based on this classification, the soils can be described as clean to slightly sandy clays. Locally higher sand contents are observed only at isolated points along the corridor. The relatively narrow spread of the PSD curves, particularly at the finer particle sizes, indicates a consistent fine-grained composition with limited variability across the investigated locations.

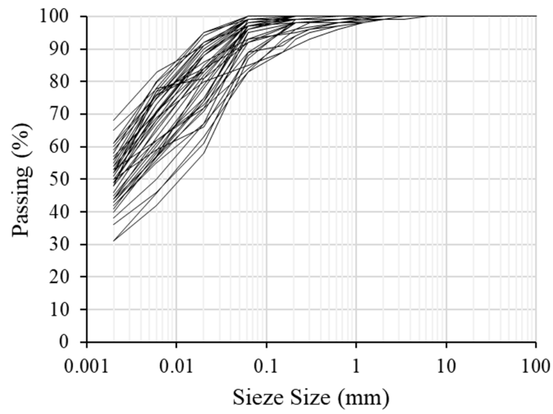

Fig 4. Particle size distribution curves for selected clay samples along the corridor.

4.3 Plasticity

Plasticity is a key classification parameter for fine-grained soils, as it is closely related to their mechanical behaviour and engineering properties. The Atterberg limits, namely the liquid limit (w_L) and the plastic limit (w_P), define conventionally established boundaries between the liquid and plastic states, and between the plastic and semi-solid states, respectively. The plasticity index (PI) represents the range of water contents over which a soil exhibits plastic behaviour and is defined as the difference between w_L and w_P.

The plasticity chart for the clay samples identified along the corridor is shown in Fig 5. This chart relates liquid limit and plasticity index to aid soil classification and assess plasticity characteristics. The data points predominantly plot above the A-line, confirming the clayey nature of the deposits. Liquid limit values generally exceed 50%, indicating high to very high plasticity clays.

Calculated liquidity index (LI) values for these samples are typically greater than 1, indicating that the in-situ moisture content exceeds the liquid limit and the clays are in a near-liquid to liquid state. Such conditions are commonly observed in very shallow offshore marine clays and are consistent with both the operational challenges encountered during field activities and the very low undrained shear strengths measured.

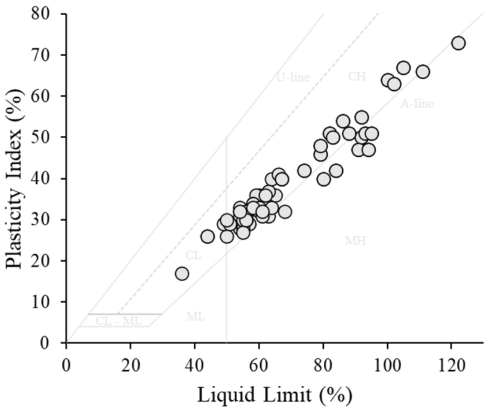

Fig 5. Plasticity chart for selected clay samples on the corridor.

4.4 Undrained shear strength

Undrained shear strength of the high plasticity, normally consolidated clay deposits was derived from CPT net cone resistance using Eq. (1, where q_n is the net cone resistance and N_{kt} is a cone factor calibrated against laboratory UU triaxial test results.

$$S_U = {}^{q_n}/_{N_{kt}} \quad (1)$$

As shown in Fig 6, a best-estimate value of $N_{kt} = 20.5$ was obtained from the correlation between CPT-derived net cone resistance and laboratory-measured undrained shear strength. This value is consistent with ranges commonly reported in the literature for normally consolidated offshore marine clays. Lunne et al. [8] suggest N_{kt} values in the range $15 - 20$ for offshore marine clays, depending on OCR, sensitivity and strain rate [8]. Mayne [9] recommends $N_{kt} = 20 \pm 5$ for normally consolidated clays [9], while Lunne and Andersen [10] report values of approximately $18 - 22$ for soft offshore clays in the North Sea [10].

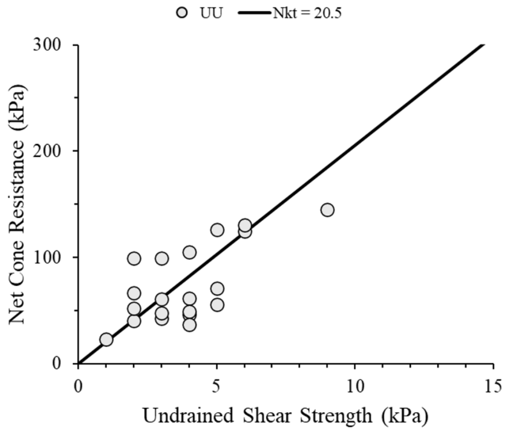

Fig 6. Best estimate N_{kt} factor for shallow marine clay.

The undrained shear strength profiles derived from CPT data using Eq. (1 are shown in Fig 7, together with the best-estimate undrained shear strength profile for the shallow marine clay deposit. The resulting best-estimate profile can be expressed by the following relationship:

$$S_U = 1.0 \text{ kPa} + 0.214 \cdot \sigma'_v \quad (2)$$

where σ'_v is the effective vertical stress, calculated using a submerged unit weight $\gamma' = 4.5 \text{ kN/m}^3$, based on laboratory unit weight measurements on the clay samples. The resulting ratio between undrained shear strength and effective overburden stress ($S_U/\sigma'_v = 0.214$) is consistent with published correlations for normally consolidated clays [9,10].

Despite this consistency with literature trends, the absolute values of undrained shear strength indicate that the marine clay at the seabed exhibits extremely low strength. The reliability of these low strength values was carefully assessed: laboratory testing was performed in accordance with relevant standards by an experienced contractor, with no reported non-conformities. Furthermore, the results are consistent with independent estimates obtained from CPT correlations, fall cone, pocket penetrometer and torvane measurements. This interpretation is also in agreement with the measured plasticity and liquidity index values and provides a clear explanation for the bearing capacity issues encountered by the seabed frame during execution of the geotechnical site investigation.

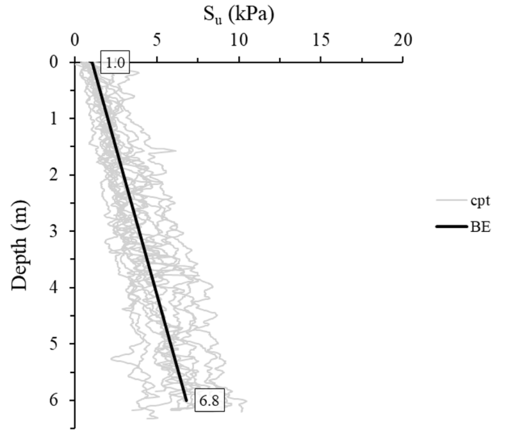

Fig 7. Undrained shear strength profiles derived from CPT data, and best-estimate profile for the shallow marine clay.

The sensitivity of the marine clay deposit was evaluated based on laboratory fall cone tests results obtained on intact and remoulded clay samples. The results are presented in Fig 8 together with a best-estimate sensitivity value of $S_t = 2.5$. Only a limited number of data points indicate sensitivity values exceeding 4.0. Overall, the clay deposit can therefore be classified as having low to moderate sensitivity, in agreement with the soil behaviour interpretation inferred from the Robertson classification chart.

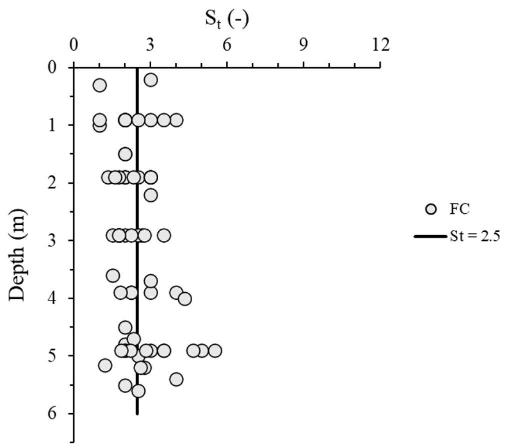

Fig 8. Sensitivity profile derived from laboratory fall cone tests on intact and remoulded samples, and best-estimate sensitivity value.

5 Conclusions

This paper presented a case study from an offshore geotechnical site investigation conducted in the Baltic Sea, integrating geological understanding, geophysical interpretation and geotechnical data to characterise conditions along an export cable route. The regional geological setting, shaped by repeated glaciations, results in a stratigraphic framework characterised by Holocene and post-glacial marine sediments overlying glacial till. Geophysical survey data confirmed this conceptual model and provided a stratigraphic basis for planning the subsequent geotechnical investigation.

The geotechnical site investigation encountered significant operational challenges due to the presence of extremely soft marine clays at mudline. The initial integrated CPT-sampling system, while appropriate from an operation and health and safety perspective, proved unsuitable under the prevailing ground conditions due to insufficient bearing capacity and stability upon seabed landing. Mitigation measures, including the deployment of independent CPT and piston coring systems, allowed the investigation to be completed, albeit with limitations and an extension of the original investigation timeline due to equipment reconfiguration and re-mobilisation.

Geotechnical characterisation of the shallow sediments showed that the marine clays are high to very high plasticity, exhibit liquidity indices typically greater than unity, and are characterised by extremely low undrained shear strength in the upper several metres. These properties explain the observed operational difficulties and highlight the challenges associated with working in similar soft-soil offshore environments.

From an installation perspective, the presence of extremely low-strength clay at seabed level may present challenges for export cable installation, particularly with respect to the bearing capacity required for installation equipment and temporary seabed support systems. Careful consideration of equipment selection and alternate installation methodologies may therefore be required in similar geological settings.

Several lessons learned can be drawn from this investigation: where soft marine sediments are anticipated, the availability of alternative or back-up geotechnical equipment on board the survey vessel may reduce the risk of double mobilisation and programme delays. Adequate schedule contingency should be included to accommodate potential operation challenges without impacting key project milestones. Finally, allowing sufficient time between completion of geophysical surveys and execution of geotechnical investigations is essential to enable robust initial interpretation and informed selection of appropriate geotechnical equipment and methodologies.

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