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Use of acoustic data to complement CPTu in identifying a significant soil layer for fjord sediments

Utilisation de données acoustiques pour compléter celles du CPTu dans l'identification d'une couche significative de sol des sédiments du fjord

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ABSTRACT: World's longest floating bridge, with 5 km length, is planned to cross the 570 m deep fjord Bjørnafjorden in western Norway. The bridge is designed with mooring systems connecting it to anchors on the seabed. Detailed investigations mapping the seabed identified up to 45 historic submarine slides. Sub-bottom profiling data was used to interpret these slides and their slip planes. These slip planes align with a soil layer distinctly visible from acoustic data. The question is whether it is possible to identify this layer with only geotechnical data, particularly CPTu/SCPTu. Current geotechnical methods adopted to establish soil layering, as recommended by a regulatory standard and various CPTU based soil behaviour classification charts, are investigated. This work shows that these approaches overlook this important layer. By revisiting CPTu/SCPTu measurements in relation to acoustic data, this work established trends and proposed approaches that could identify this slip plane consistently. This approach ensured that the information from geotechnics and geology complement each other in identifying significant layers. This work illustrates that combining acoustic and CPTu data improves geotechnical interpretation and understanding of critical ground conditions.

RÉSUMÉ : Le plus long pont flottant du monde, d'une longueur de 5 km, est planifié pour traverser le fjord Bjørnafjorden, d'une profondeur de 570 m, dans l'ouest de la Norvège. Le pont est conçu avec des systèmes d'amarrage le reliant aux ancrages au fond marin. Des études détaillées sur la cartographie des fonds marins ont permis d'identifier jusqu'à 45 glissements de terrain sous-marins historiques. Les données de profilage du fond marin ont été utilisées pour interpréter ces glissements et leurs plans de glissement. Ces plans de glissement s'alignent avec une couche de sol clairement visible à partir des données acoustiques. La question est de savoir s'il est possible d'identifier cette couche avec uniquement des données géotechniques, en particulier CPTu/SCPTu. Les méthodes géotechniques actuelles adoptées pour établir la stratification du sol sont respectées. Cette étude montre que ces approches négligent cette couche importante. En réétudiant les mesures CPTu /SCPTu en relation aux données acoustiques, ce travail a établi des tendances et proposé des approches qui pourraient identifier ce plan de glissement de manière cohérente. Cette approche a permis de garantir que les informations issues de la géotechnique et de la géologie se complètent pour identifier les couches importantes.

KEYWORDS: Soil layering, submarine slide, slip plane, CPTu, acoustic data.

1 INTRODUCTION

The route from Kristiansand in the south Norway to mid-Norway Trondheim in the north is approximately 1100 kilometres long and currently consists of eight ferry crossings. The Norwegian parliament, Storting, has a long-term goal to develop this route as an improved and continuous coastal highway route. To realise this, the Norwegian Public Roads Administrations (NPRA) is working on plans to upgrade the E39 route to become a ferry free highway. When completed, the project substantially reduces the current travel time of 21 hours as well as provide improved safety and connectivity of adjacent regions. Bridges or tunnels shall be constructed to cross several fjords that currently need ferry connections. One of the fjords located on the southwestern coast of Norway, Bjørnafjorden, is 5 km long and 570 m deep. After comprehensively studying various concepts, the NPRA concluded on a 5 km long floating bridge as the most viable solution to cross Bjørnafjorden. When constructed, the Bjørnafjorden bridge will be the longest floating bridge in the world. This significantly surpasses the current longest floating bridge, the 2.35 km long Evergreen Point floating bridge crossing the 65 m deep lake Washington in Seattle, USA.

The width and the depth of the Bjørnafjorden fjord provide a formidable engineering challenge that demands innovative solutions both for structural design and construction methods. Of the various floating bridge concepts considered for Bjørnafjorden, a curved end-anchored floating bridge moored to side anchors is selected for further design considerations. This solution utilises a mooring system for increased robustness and redundancy. This means that selected pontoons distributed along the floating bridge are moored to anchors on the seabed. The proposed concept is illustrated in Figure 1. The mooring system is designed to be used on both sides of the bridge, and the schematic in Figure 1 illustrates the system at one side. In total, 12 to 16 anchors are required for the currently considered design. In identifying the specific anchor locations, it is vital to identify risks related to geological and geotechnical conditions related to foundation conditions and possible subsea slides. In this context it is important to have a thorough understanding of the subsea ground conditions such as topography, soil layering and soil characteristics. Detailed survey is carried out with geophysical and geotechnical investigations (DOF 2016, 2018; NGI 2016, 2019a).

Bathymetry data from Bjørnafjorden reveals a variable seabed condition. The fjord is asymmetrical with undulating seabed

(Figure 1). On the northern side, there is more exposed bedrock, some submarine elevations and plateaus. In the south, the inclination down to the basin is steeper and less variable. Sediments appear in the basins and the troughs. In the central part of the fjord there are some raised areas due to undulating bedrock. The sediment thickness in Bjørnafjorden varies from 0 m at bedrock outcrops to 80 m in the deepest part of the fjord. The sediments are generally homogeneous throughout the crossing area and the soil can be described as a marine clay with extremely low shear strength at seabed, increasing to medium/high shear strength with depth. At the bottom of the boreholes a thin layer of hard sandy silty clayey material is encountered above the rock surface. A detailed description of sediments is given in section 3.

Main aspect of the results given in this paper, have previously been presented at the Nordic Geotechnical Meeting (Degago et al. 2020). However, in the current paper, the work is enhanced, extended to include other data such as seismic data as well as feedbacks on previous work. It is thus presented in this conference with an aim to reach to a broader Geotechnical community at a bigger international conference.

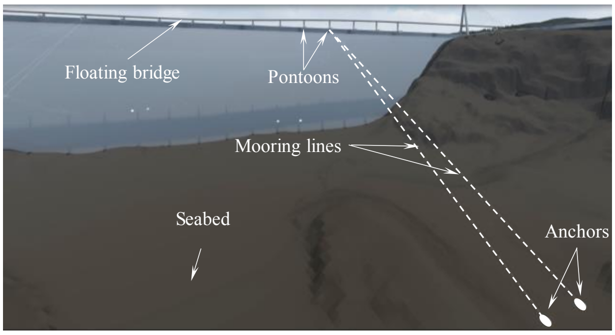


Figure 1. Illustration showing part of the floating bridge connected to anchors on seabed with mooring lines (Illustration: Modified after NPRA 2019a).

2 GEOLOGICAL CONDITIONS

Bjørnafjorden is a relatively typical fjord, in a geological point of view. Fjords are over deepened troughs created by interchanging river and glacial erosion. The river erosion follows bedrock structures above sea level whilst glaciers erode the bedrock below sea level. The sediments in Bjørnafjorden were reworked and eroded when the glacier advanced over the fjord. Traces of this process is seen as till just above bedrock. During the deglaciation, marine clay was deposited as meltwater plumes. These deposits are commonly seen as acoustically laminated deposits (Aarseth, 1997). After the first deglaciation, the cold Younger Dryas period caused a readvance of the ice, placing the ice front about 9 km northwest of the bridge crossing area. The seasonal melting caused deposition of glacimarine clay. These deposits are seen in the acoustic data as dark acoustically laminated deposits (Solli et al. 2017). Following the Younger Dryas, the continent rose (isostatic rebound), causing lower sea level and earthquakes, both factors contributing to many slope failures. Several slope failure events have occurred in Bjørnafjorden during the current interglacial period, the Holocene (the past 11 000 years), and the slide events before about 8 000 years ago coincided with a period with isostatic rebound and sea level changes (Lohne et al. 2007). However, there are also many slide events younger than 8 000 years in Bjørnafjorden. The slide events in this period are considered to have been triggered by smaller earthquakes, and possibly gradual sediment build-up, which are conditions relevant for the current time and the near future (Lohne et al. 2007).

The topography, sediment thickness and engineering characteristics indicate that there still is potential for future submarine slides due to several marginally stable slopes (Carlton et al. 2018). These slides may affect anchors since the anchors could be within the initial slide zone or experience impact force by a slide run-out. Accordingly, submarine slope instabilities are identified as the main geohazard for the bridge across Bjørnafjorden. Other factors, than geohazard, govern possible anchor locations which include foundation conditions, symmetry conditions for the bridge and the required angle and length of the mooring lines. This implies that it is necessary to deal with submarine slides as possible geohazards, where several considerations are made, including assessing stability under design loads, estimating the resulting impact force from submarine slides on anchors and then designing the anchors to withstand these forces. In this context, significant effort was made to improve understanding of the slide mechanisms, through e.g., mapping, modelling and dating of historical slide events (e.g., Solli et al. 2017; NPRA 2019b; Carlton et al. 2018).

The main aspect presented in this paper is identifications of the soil layering and the soil properties that are essential for submarine slides. Special emphasis is placed on the complementary information provided by combining geophysical and geotechnical investigations.

3 GROUND INVESTIGATIONS OF BJØRNAFJORDEN

Extensive ground investigations are carried out in Bjørnafjorden to map the seabed (e.g., DOF 2016, 2018; NGI 2016, 2019a, 2019b). A brief overview is given in this section.

3.1 *Geological seabed mapping*

The geological seabed mapping was performed during 2016 and 2018 by DOF (2016, 2018). The 5000 m long bridge crossing area was mapped in a 3500 m wide corridor with 50 m grid spacing. The acoustic equipment utilized in 2016 was sub bottom profiler (SBP), side scan sonar and multibeam echosounder. The north-south lines and a few east-west lines were mapped with equipment fitted on a remotely operating vehicle (ROV). The ROV had a 25 m fly height allowing for bathymetry grid cells of 0.5 m^2. The SBP data was collected with frequencies providing high vertical resolution (about 0.3 m). Using an ROV significantly reduced the uncertainty from side echo on the SBP data. The east-west lines were mapped with hull mounted equipment, using frequencies for deeper penetration on the SBP data. Additional details about the method and the overall results are given in Solli et al. (2017).

The geophysical survey in 2018 used the same acoustic instruments, only fitted on an autonomous underwater vehicle (AUV) with a 40 m fly height. The depth calculation of the SBP data is performed with a two-way travel time of 1500 m/s. Based on correlation between acoustic data and bore holes, the depth uncertainty is about 0.5 m on flat areas. Side effects cause larger acoustic uncertainties on the sloping areas, and the uncertainty increases with the steepness. At the bottom of slopes the sediment thicknesses were often underestimated in the acoustic interpretation. The various geophysical data were used as a basis to identify borehole and core locations, both for geotechnical investigations (NGI 2016, 2019a) and geological purposes. Fifteen gravity cores were retrieved in 2017 and 2018 (length from 1 to 5 m below seafloor). Selected intervals were radiocarbon dated to estimate the timing of past slide events. These results are presented in NPRA (2019b).

3.2 *Geotechnical investigations*

Geotechnical soil investigations were first carried out in 2016 with 5 boreholes comprising soil sampling and CPTu to provide data for the early concept evaluation phases (NGI, 2016). A detailed soil investigation scheme was carried out in 2019 with further 22 boreholes aiming for subsequent detailed bridge design (NGI 2019a). The purpose of these boreholes was to characterize the soil sediments at locations relevant for the planned anchor foundations as well as to study potential subsea slides that may include or affect nearby anchors. As a result, these boreholes are spread over the fjord basin (NGI, 2019a). The geotechnical field investigations carried out include 19 CPTu, 8 SCPTu (seismic CPTu), pore pressure dissipation test at two depths at 3 positions, and 11 soil sampling locations. The field work was carried out by Fugro and the laboratory testing was run both offshore and at NGI's laboratory facilities in Oslo. All borings were stopped once a hard layer with a cone tip resistance exceeding 2 MPa was encountered. The end of the borehole at each location is assumed to be a hard layer, possibly till or bedrock. Samples were taken from the seafloor down to a maximum depth of 46 m below seafloor. Results of the investigations indicated that the soil consists of marine clay with extremely low to medium undrained shear strength.

Based on test results, the soil layering was identified through a set of "unit layers" with defined characteristics. In the present study, emphasis is given on the boundaries of a soil layer referred to as Unit 3. The representative parameters for three soil layers designated as above (from seabed to top of unit 3), unit 3 and below (from bottom of unit 3 to end of borehole) are presented in Table 1 along with symbol abbreviations defined below the table. The overconsolidation ratio varies from 4.2 at the top to 1.2 at the bottom of the layer. The fines content (silt and clay) of the layer is 96–98 % where the clay content is 49–53%. Unit 3 exhibit higher sensitivity (S_t) as compared to the soil layers above and below. Additional and detailed experimental results can be referred to NGI (2019b).

Table 1. Representative soil parameters from various units

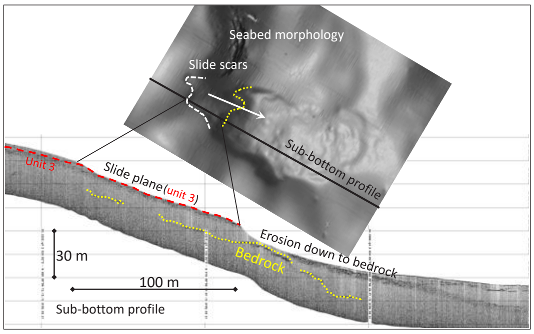
Layer	γ	w	I_p	$S_{u,\,rem}$	S_t
	(kN/m^3)	(%)	(%)	(kPa)	-
Above	14–16	110–76	70–45	1.1–5.8	2.5
Unit 3	16–17	62–47	27–45	0.9–2.5	4.5–11
Below	16–18	61–48	45–40	1.3–13.0	4.0

γ is unit weight; w is water content; I_p is plasticity index; $S_{u,\,rem}$ is remoulded shear strength and S_t is soil sensitivity.

4 KEY OBSERVATIONS FROM PAST SUBMARINE SLIDES

The acoustic data from Bjørnafjorden revealed typical fjord characteristics, with till, glacimarine deposits and slides (Aarseth 1997, Kjennbakken et al. 2017). In Bjørnafjorden 45 submarine slides were identified (DOF 2016, 2018, Solli et al. 2017). The sub-bottom profiling data was used to interpret past slide events and their slip planes. Radiocarbon dating of marine carbonate (benthic foraminifera) was used to identify the timing of the slide events (NPRA 2019b, Kjennbakken et al. 2017). It is worthwhile to mention that based on the soil investigations carried out in 2016, numerical back calculation of past submarine slides from Bjørnafjorden are performed (Carlton et al. 2018, Kjennbakken et al. 2017).

Submarine landslides often develop along seismic horizons or within specific soil units (e.g., Bryn et al. 2005, Vanneste et al. 2014). This also seems to be the case in Bjørnafjorden. The acoustic interpretation of past slide events showed that all recorded slide events either eroded down to bedrock or had their slip plane at a dark acoustic horizon. This acoustic horizon is representing a soil layer and is referred to as unit 3. The layer is found over the entire basin and on most of the sloping areas (< 30 degrees). The role of this layer on past slides is illustrated using sub-bottom profile of two submarine slides in Figure 2. For



similar illustrations and detailed description of the various geological units, reference is made to Kjennbakken et al. (2017). Key observation, from examining past slides, is that the unit 3 layer is seen to be crucial in understanding past slides and thus to study future submarine instabilities, Figure 2.

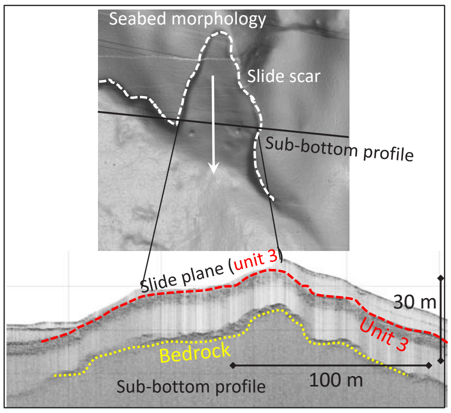


Figure 2. Different soil units and bed rock interpreted from acoustic data and submarine slides

5 SOIL LAYERING FROM ACOUSTIC SURVEY DATA

Considering submarine slides, the most interesting layer is the dark acoustically laminated horizon, reflecting the Younger Dryas (YD) glacimarine deposits (Kjennbakken et al. 2017). Four profiles located near geotechnical borehole locations are selected to illustrate the layering as identified from the acoustic data. They are given in Figure 3. As can be seen in all acoustic profiles, the start of unit 3 is distinctly visible and this is indicated as “YD boundary/unit 3” in the figures. Unit 3 starts at different sediment depths across the basin and the interpreted top of unit 3 are estimated as following: BH-1 (15.25 m +/- 0.25 m), BH-5 (~11 m). BH-13 (5 m +/- 0.5 m) and BH-19 (6.75 m +/- 0.25 m).

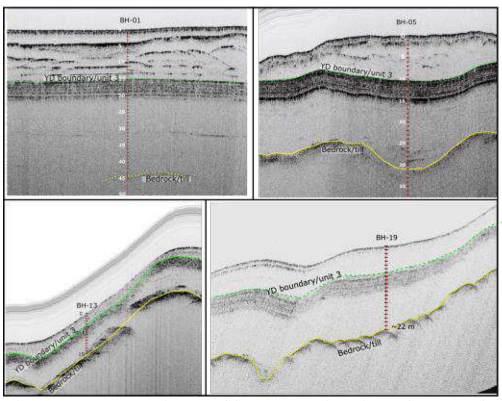


Figure 3. Acoustic profiles around selected geotechnical borehole locations (BH-01, 05, 13 and 19) (Scale 1H:4V)

6 SOIL LAYERING FROM GEOTECHNICAL INVESTIGATIONS

In section 4, top of unit 3 is identified as the acoustic horizon reflecting slip plane of past submarine slides. A key question is; if there had not been any acoustic data available, would it be possible to identify this slide plane and geological unit with only CPTu borings? This section attempts to answer this question as well as to address how layering interpretation based on acoustic and CPTu correspond with each other.

In geotechnical practice, detailed soil stratigraphy is often established based on continuous sampling and/or CPTu borings. Acquiring continuous sampling is expensive and CPTu data is considered to provide a key input due to continuity in in-situ measurements along the depth profile. Currently, there exist different methods or practices for determining soil layering from CPTu data. One way is by adopting soil layering and description according to NS-EN ISO standard 14688-2 (2018). Another alternative is to identify layering based on soil behaviour classification charts (e.g., Robertson et al. 1986, Robertson 1990, Eslami & Fellenius 2000, Schneider et al. 2012). These two approaches are selected to illustrate their capability to identify soil layering as observed in the acoustic data.

6.1 *Soil layering based on NS-EN ISO Standard*

One common way to establish description of soil layering in offshore is according to the standard NS-EN ISO 14688-2 (2018) as given in Table 2. Accordingly, undrained shear strength interpreted from CPTu (along with samples whenever available) can be used in classifying typical layers. In this project, cone factors are calibrated based on laboratory data to provide local correlations and used for boreholes without sampling (NGI, 2019b). The interpreted undrained shear strength values are used to classify soil layers based on NS-EN ISO standard. The resulting layer boundaries are shown in Figure 5 (using broken lines). To enable comparisons, the start of unit 3 as interpreted from acoustic data (Figure 3) is given in the Figure 5 with a red band crossing the figure. It can be seen that layering based on NS-EN ISO standard gave a reasonable layer location for unit 3 for BH-1. However, the method was unable to identify top of unit 3 in the other three cases, resulting in layer boundaries being significantly off. The main reason for this is that the values defining the boundaries (Table 2) are somewhat arbitrary and probably meant to provide a pragmatic way of defining layering. This explains why this interpretation approach (NS-EN ISO) was unable to consistently capture unit 3 in Bjørnafjorden, Figure 5. Soil layer classifications based on Table 2 are generally useful to get an overall picture of the ground condition. However, the resulting layering would probably be significantly improved if the method was revised to specify limits of undrained shear strength relative to effective overburden pressure at the depth, rather than the absolute undrained shear strength values.

Table 2. Soil layering description according to NS-EN ISO 14688-2 (2018).

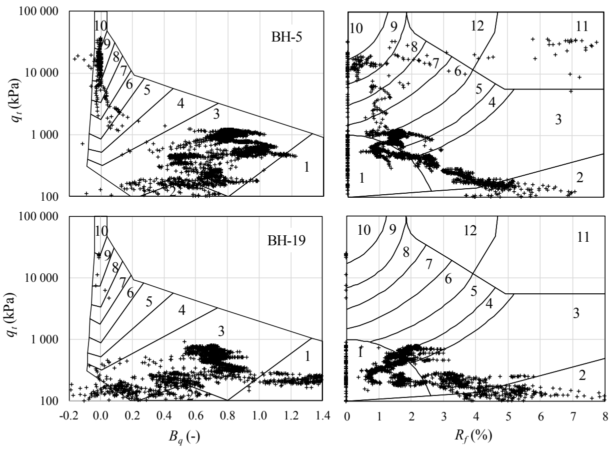
Soil description	Undrained shear strength of clays (kPa)	Soil description	Undrained shear strength of clays (kPa)
Extremely low	< 10	Medium	40 to 75
Very low	10 to 20	High	75 to 150
Low	20 to 40	Very high	150 to 300
		Extremely high *	> 300

*Materials with shear strength greater than 300 kPa may behave as weak rock. Can be described according to ISO 14689-1

6.2 *Soil layering from soil behavior type classification charts*

Another common way used to identify soil layering from CPTu is based on soil behaviour type (SBT) classification charts that link CPTu measurements with behaviour of soil type (e.g., Robertson et al. 1986, Robertson 1990, Eslami & Fellenius 2000, Schneider et al. 2012). These SBT charts are useful, especially in absence of sampling, to indicate how the soil behaves in terms of its physical and mechanical properties. SBT classification charts are usually based on calibration of derived parameters from CPTu measurements in known soil types. The direct measurements from CPTu are the cone tip resistance (q_c), sleeve friction (f_s), and pore pressures measured behind the cone shoulder (u_2). However, it is normalized parameters that are commonly used for SBT classifications charts and the most common parameters include friction ratio ($R_f = f_s/q_n$) and pore pressure ratio ($B_q = (u_2 - u_0)/q_n$) where q_n is the net cone resistance ($q_n = q_t - \sigma_{v0}$), q_t is the total cone tip resistance corrected for unequal end areas; σ_{v0} is the total vertical stress; u_0 is the in situ pore pressure.

In this study selected SBT classification charts (Robertson et al. 1986, Robertson 1990, Eslami & Fellenius 2000, Schneider et al. 2012) are assessed using the spreadsheet program developed at NPRA by Valsson (2019). These charts were evaluated based on their ability to identify behavioural change around start of unit 3. However, almost none of the SBT charts indicated a behavioural change around unit 3. One possible reason for this could be the fact that these SBT classification charts are not calibrated using data from the present soil type. The SBT chart proposed by Robertson et al. (1986) is selected for presentation in this study as it looked better at indicating changes around unit 3 as compared to the other charts. The SBT charts based on B_q and q_t (to the left) and based on R_f and q_t (to the right), are given for data points from BH-5 and BH-19, in **Error! Reference source not found.**. For a given CPTu boring data, it is noticed that the distribution of data into the various soil behaviour classes is different between the two methods, **Error! Reference source not found.**. These classifications are given along with depth profile, for the four borings, in Figure 5.



Soil behaviour type (zone): Sensitive fine grained (1); Organic material (2); Clay (3); Silty Clay to clay (4); Clayey silt to silty clay (5); Sandy silt to clayey silt (6); Silty sand to sandy silt (7); Sand to silty sand (8); Sand (9); Gravelly sand to sand (10); Very stiff fine grained (11); Sand to clayey sand (12).

Figure 4. SBT chart by Robertson et al. (1986) based q_t and B_q (to the left) and q_t and R_f (to the right) for BH-5 (top two) and BH-19 (bottom two).

From Figure 5, it is observed that the SBT chart based on R_f and q_t indicated a layer with behavioural change around unit 3. The chart described the behaviour of this layer as "sensitive fine-grained". It gave a good match for start of unit 3 for BH-19. Still, the method is not completely consistent as it also interprets this behaviour above unit 3, making it a challenge to precisely identify the start of unit 3, see results of BH-1, BH-5 and BH-13. It is noted that the SBT classification chart by Robertson et al. (1986) based on B_q and q_t did not indicate the same behavioural change around unit 3 except for BH-19 where it was vague. This does not, however, imply that the B_q behaviour is not important in identifying the layer. In fact, by investigating the CPTu profiles visually it is observed that the B_q depth profile displays a noticeable shift while penetrating though unit 3. This indicates that the CPTu results provide the relevant information, but the classification chart does not properly differentiate this change in B_q. Revised charts for this soil type could be developed in future.

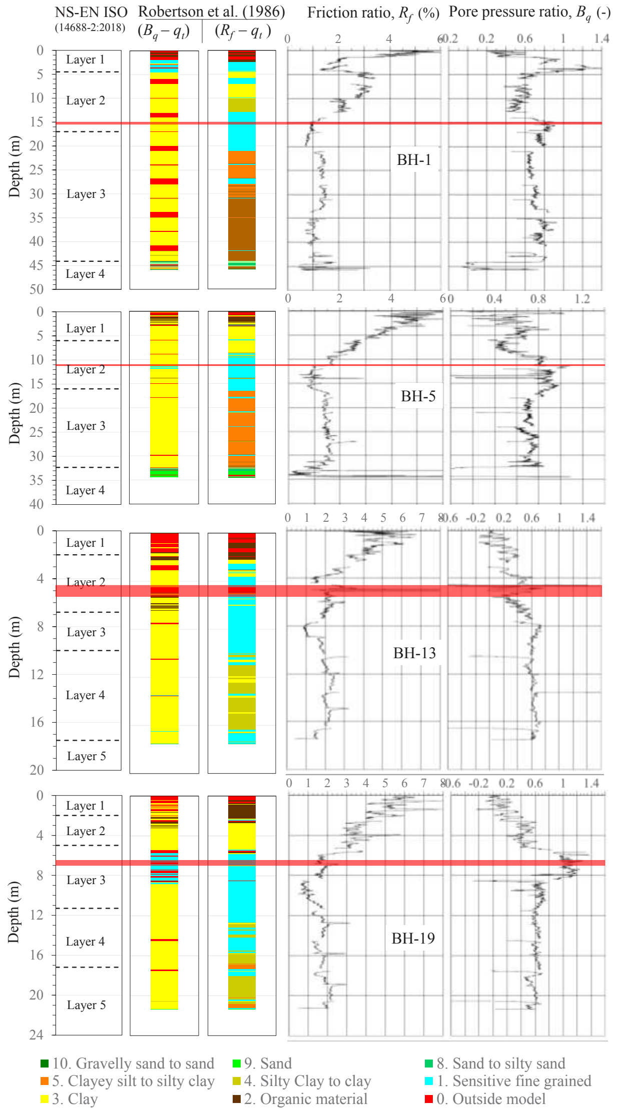


Figure 5. Soil layering based on NS-EN ISO (to the left), SBT charts (coloured columns in the middle) as well as selected CPTu data (q_t , R_f and B_q). Based on acoustic data top of unit 3 is interpreted to be within the indicated red band crossing the figure.

7 REVISITING CPTU DATA CONSIDERING ACOUSTIC DATA

The previous section elaborated that unit 3 was not satisfactorily identified with the NS-EN ISO standard and SBT classification charts. In this section, direct CPTu measurements (q_c, f_s, u_2) as well as derived parameters (q_t, R_f, B_q) are examined to identify trends that match with top of unit 3. For SCPTu tests the interpreted shear wave velocity is also considered.

The first parameter looked at is undrained shear strength interpreted from CPTu based on corrected tip resistance q_t. In some boreholes it was observed that the undrained shear strength tends to drop when entering unit 3. However, this was not consistent and clearly visible in other CPTu borings, making identification of unit 3 based on undrained shear strength alone challenging. A probable reason for this insensitivity could be the large total stress at such water depth as compared to the small values of q_t. Results of q_t inlight of the acoustic data can be seen from Degago et al. (2020).

One logical measurement to look at is seismic data from the limited bore holes where SCPTu were carried out (NGI 2019b). Using a dual seismic cone penetrometer, shear wave velocities (v_s) were interpreted using the two sets of geophones 0.5 m apart with the lower geophone positioned 238 mm above the cone base. Recording of shear wave traces was performed at every 1.5 m depth. Thus, it was not a continuous v_s measurement, and this makes it challenging to precisely identify a change in measurement when entering unit 3. The darker layer below YD-boundary as seen in the acoustic data, indicates a change in the impedance contrast and reflection coefficient, which may result from changes in the lithology. Shear wave velocity measurements from BH-13 and BH-19 are given in Figure 6 along with start of unit 3 interpreted from acoustic data. As can be seen from the plot, the v_s measurement data did not show any significant or consistent change when entering unit 3. However, there is a tendency to have lower v_s just before the start of unit 3 which tended to increase below this level. The v_s interpreted based on q_t also supports this observation.

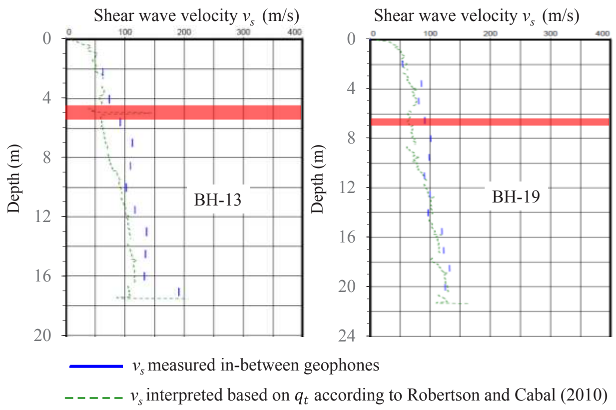


Figure 6. Shear wave velocity measured and interpreted based on q_t in BH-13 and BH-19 (after NGI 2019a). The red band indicates the start of unit 3 as interpreted from acoustic data.

After investigation of q_t and v_s ,which did not reveal any trend with respect to acoustic data, the study focused on examining trends of the commonly derived parameters. This is done by visual observation of depth profiles to find any possible trend at a depth where unit 3 starts. The study revealed interesting trends in the depth profiles of pore pressure ratio (B_q) and friction ratio (R_f) from the borings. It was observed that these two derived parameters exhibit shift in the curves when entering unit 3, Figure 5. The pore pressure ratio tends to show a relative increase in this unit. The friction ratio was observed to start higher and continuously decrease into a more or less constant value when entering unit 3, thus the transition of friction ratio into somewhat constant trend matched with the top of unit 3 from acoustic data. These trends are thus established to identify top of unit 3. One borehole that is a bit uncertain with this regard is BH-

13 where the depth to the top of unit 3 can be somewhat different as compared to the nearest acoustic profile. The reason for this could be that BH-13 lies 20 m away from the nearest acoustic profile and at the same time located in a sloping ground (see also Figure 3). Otherwise, the established trends of B_q and R_f in identification of unit 3 are very distinct for BH-1, BH-5 and BH-19 where the acoustic profiles are closest to the corresponding bore holes. This is illustrated in Figure 5. It is worthwhile to mention that evaluation of other CPTu data in the project, revealed similar trends as exemplified by the selected four CPTu data given in this article. All these observations shall be compiled in a report for use in the project.

8 FINAL REMARKS

Submarine slides are considered as the main geohazard in Bjørnafjorden. Based on interpretation of past submarine slides, an important soil layer is distinctly identified from acoustic data. This layer coincides with the slip failure zone of several historical landslides and is considered important when evaluating geohazard related to potential future submarine slides. However, this work illustrated that current geotechnical approaches used to establish soil layering overlook this important layer.

This work evaluated various CPTu data in relation to acoustic results to establish trends that could identify this slip plane. Identification of this significant soil layer from CPTu is improved with acoustic data and an approach for this is also proposed. A combination of R_f and B_q is shown to consistently capture this layer as observed in acoustic data. This approach ensures that the information from geotechnics and geology complement each other in identifying layers significant for slope stability evaluations. The method proposed in this work can also be used in cases where no acoustic data exists.

Geophysical surveying over large areas has a much lower cost than a sufficiently dense mesh of traditional geotechnical surveys/borings to decide soil layering. For large areas, like Bjørnafjorden, combining geotechnical investigations with acoustic data in soil layering identification gives better basis for accurate slope stability analyses, at a significantly lower cost. In doing so, it is important to first establish ways to create synergy between geotechnical and geophysical data. This work illustrates that combining acoustic and CPTu data improves the interpretation and understanding of critical ground conditions. The approach presented in this work is considered valuable also for other marine sediments.

The approach presented here is mainly based on visual observation of trends of data. Still, it was seen to give very good agreement between CPTu and acoustic data. By collecting more data including from other fjords, a more sophisticated layer classification system could be established. One promising approach to do this is based on machine learning. This method has a potential to give an objective and powerful way of identifying layering in such fjords and is considered as a future work.

9 ACKNOWLEDGEMENTS

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10 REFERENCES

Aarseth I. 1997. Western Norwegian fjord sediments: Age, volume, stratigraphy, and role as temporary depository during glacial cycles. *Marine Geology* 143, 39–53.

Bryn P., Berg K., Stoker M. S., Haflidason H. and Solheim A. 2005. Contourites and their relevance for mass wasting along the Mid-Norwegian Margin. *Marine & Petroleum Geolo.* 22, 85–96.

Carlton B., Vanneste M., Forsberg, C. F., Knudsen S., Løvholt F., Kvalstad T. J., Holm S., Kjennbakken H., Mazhar M. A., Degago S. A. and Haflidason H. 2018. Geohazard assessment related to submarine instabilities in Bjørnafjorden, Norway. In Mosher, D. C. et al., eds., Subaqueous Mass Movements and Their Consequences: *Geological Society, London, Special Publications, 477*, 549-566, https://doi.org/10.1144/SP477.39

Degago S. A., Kjennbakken H, Kavli A. and Want A. 2020. Improving identification of a significant soil layer from CPTU combined with acoustic data. Nordic Geotechnical Meeting (NGM).

DOF 2016. Bjørnafjorden Survey report, Documnt no. 600308-SV-CL-403-0001. DOF Subsea.

DOF 2018. Bjørnafjorden Survey report, Document no. 1003293-SV-CL- 403-0002. DOF Subsea.

Eslami A. and Fellenius B. H. 2000. Soil profile interpreted from CPTu data. "Year 2000 Geotechnics", Geotechnical Engineering Conference, Asian Institute of Technology, Bangkok, Thailand, November 27 - 30, 18 p.

Kjennbakken H., Mazhar M. A., Degago S., Schrøder K. and Haflidason H. 2017. Mapping and modelling of subsea slides in Bjørnafjorden, Western Norway. In: Dunham, K.K., Dammyr, Ø, Rømoen M. and Engen S. (eds) Geoteknikkdagen. Norsk Geoteknisk Forening, Oslo.

Lohne Ø. S., Bondevik S., Mangerud J., Svendsen J. I. 2007. Sealevel fluctuations imply that the Younger Dryas ice-sheet expansion in western Norwegy commenced during the Allerød. *Quaternary Science Reviews* 26, 2128-51.

NGI 2016. Bjørnafjorden 2016 Soil Investigation. Field Operations and Preliminary Results. NPRA Doc. No. SBT-PGR-RE-203-008-1.

NGI 2019a. E39 Bjørnafjorden 2019 Soil Investigation. Field Operations and Preliminary Results. NPRA Doc. no. SBJ-02-C5-NGI-02-RE-001.

NGI 2019b. E39 Bjørnafjorden 2019 Soil Investigation. Measured and Derived Geotechnical Parameters and Final Results. NPRA Doc. no. SBJ-02-C5-NGI-02-RE-002.

NPRA 2019a. The E39 Coastal Highway Route: Illustrations. [Image on internet]. [updated 06.08.2019; cited 27.05.2021]. Available at https://www.vegvesen.no/vegprosjekter/ferjefriE39/illustrasjonar.

NPRA 2019b. Dating of slide events in Bjørnafjorden. In collaboration with University in Bergen (UiB). Report under final stage.

NS-EN ISO 14688-2 2018. Geotechnical investigation and testing. Identification and classification of soil– Part 2: Principles for a classification.

Robertson P. K., Campanella R. G., Gillespie D. and Greig J. 1986. Use of Piezometer Cone data. Use of In-situ testing in Geotech. Engng. GSP 6, *ASCE, Specialty Pub*, 1263-1280.

Robertson P. K. 1990. Soil classification using the cone penetration test. *Canadian Geotechnical Journal*, 27 (1), 151-158.

Robertson, P.K. and Cabal, K.L. 2010. Guide to Cone Penetration Testing for Geotechnical Engineering. 4thed., Signal Hill: Gregg Drilling & Testing.

Schneider J. A., Hotstream J. N., Mayne P. W. and Randolph M. F. 2012. Comparing CPTU Q-F and Q-$\Delta u2/\sigma'_{v0}$ soil classification charts. *Géotechnique Letters* 2, 209–215.

Solli K., Vikebø J.A., Søyland E., Hjelstuen B.O., Kjennbakken H. and Thomassen T. 2017. Detailed site survey examining the postglacial sediment succession and depositional processes within a Norwegian fjord system, Bjornafjorden (West Norway). *Norw. J. of Geology* 97, 95–104.

Valsson 2019. CPTu interpretation and presentation spread sheet developed by NPRA, Ver. 2019.061. Available at https://www.vegvesen.no/fag/teknologi/geofag/Geoteknikk/cptu.

Vanneste M., Sultan N., Garziglia S., Forsberg, C. F. and L'heureux J.-S. 2014. Seafloor instabilities and sediment deformation processes: the need for integrated, multi-disciplinary investigations. *Marine Geology* 352, 183–214.