Improving identification of a significant soil layer from CPTU combined with acoustic data

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Abstract. The Norwegian Public Roads Administrations (NPRA) plans to build world’s longest floating bridge with 5 km length to cross the 570 m deep fjord Bjørnafjorden. The bridge is planned with mooring systems connecting it to anchors on the seabed. The evaluation of soil condition on the seabed is crucial both for design of the anchoring systems and for the evaluation of possible slides that may affect the foundations. Detailed seabed mapping revealed variable seabed conditions and identified up to 45 historic submarine slides. Sub-bottom profiling data was used to interpret past slide events and their slip planes. The sub-bottom profiling revealed a soil layer that is distinctly visible from acoustic data. This soil layer coincides with the slip plane identified from a number of the historic slides. Identification of this layer is considered important to make more realistic slope stability evaluations. The question is whether it is possible to identify this layer with only geotechnical data, particularly CPTu data. Current approaches to establish soil layering as recommended by NS-EN ISO standard and different CPTU based soil behaviour classification charts are investigated. This work shows that these evaluation approaches do not correspond with the results from acoustic data in a consistent and reliable way. Approaches based on CPTu alone might overlook this important layer. However, by revisiting CPTu measurements in relation to the acoustic data, this work established trends in CPTU data and proposed approaches that could identify this slip plane. This approach is more consistent and ensures 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. This approach is considered valuable also for other fjord sediments.

1. Background
The Norwegian Public Roads Administrations (NPRA) plans to upgrade parts of the coastal highway E39 to become a ferry free highway. This project stretches from Trondheim in mid-Norway to Kristiansand in south-Norway, an 1100 km long stretch. When completed, it substantially reduces the current travel time as well as provide improved safety and connectivity of adjacent regions. Bridges or tunnels shall be constructed to cross several fjords that currently includes 8 ferry connections. A 5 km long floating bridge is planned to cross the 570 m deep fjord Bjørnafjorden located on the southwestern
coast of Norway. 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. After comprehensively studying various concepts, the NPRA concluded on a floating bridge as the most viable solution. Of the various floating bridges concepts, 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, such as foundation conditions and possible subsea landslides. 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 [1-4].

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.

Figure 1. Illustration showing part of the floating bridge connected to anchors on seabed with mooring lines (Illustration: Modified after NPRA [5]).

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 [6]. 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 [7]. 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 [8]. 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 [8].

The topography, sediment thickness and engineering characteristics indicate that there still is potential for future submarine slides due to several marginally stable slopes [10]. 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, such as 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 the understanding of the slide mechanisms, through e.g. mapping, modelling and dating of historical slide events [e.g. 7, 9, 10].

The main aspect presented in this paper is the 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. 1-4, 11]. 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 subsea [1, 2]. 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 m². 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. [7].

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 [3,4] 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 [9].
3.2. Geotechnical investigations

Geotechnical soil investigation was first carried out in 2016 with 5 boreholes comprising soil sampling and CPTu to provide data for the early concept evaluation phases [3]. A more detailed soil investigation scheme was carried out in 2019 with further 22 boreholes aiming for subsequent detailed bridge design [4]. The purpose of these boreholes was to characterize the soil sediments at locations relevant for the planned anchor foundations, and to study potential subsea slides that may include or affect nearby anchors. As a result, these boreholes are spread over the fjord basin [4]. The geotechnical field investigations carried out includes 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. Focus in the present study is 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. 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 [11].

Table 1. Representative soil parameters from various units

| Layer    | $\gamma$ (kN/m$^3$) | $w$ (%) | $I_p$ (%) | FC (%) | CC (%) | OCR | $S_{u, rem}$ (kPa) | $S_t$ |
|----------|----------------------|---------|-----------|--------|--------|-----|-------------------|-------|
| Above    | 14.1-15.5            | 110-76  | 70-45     | 98     | 49     | 4.2-1.7 | 1.1-5.8          | 2.5   |
| Unit 3   | 16.3-17.4            | 62-47   | 27-45     | 97     | 47     | 1.7-1.4 | 0.9-2.5          | 4.5-11|
| Below    | 16.3-18.4            | 61-48   | 45-40     | 96     | 53     | 1.4-1.2 | 1.3-13.0         | 4.0   |

$\gamma$ is unit weight; $w$ is water content; $I_p$ is plasticity index; FC is fines content (silt and clay); CC is clay content; OCR is over consolidation ratio; $S_{u, rem}$ 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 [6, 12]. In Bjørnafjorden 45 submarine slides were identified [1, 2, 7]. 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 [9, 12]. 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 [10, 12].

Submarine landslides often develop along seismic horizons or within specific soil units [e.g. 13, 14]. 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. [12]. Key observation from looking at 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.
5. Soil layering from acoustic survey data

In light of submarine slides, the most interesting layer is the dark acoustically laminated horizon, reflecting the Younger Dryas (YD) glacimarine deposits [12]. 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 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: BH1 (15.25 m +/- 0.25 m), BH5 (12 m), BH13 (5 m +/- 0.5 m) and BH19 (6.75 m +/- 0.25 m).

6. Soil layering from geotechnical investigations

In earlier sections, 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 also addresses how layering interpretation based on acoustic and CPTu correspond with each other.

In geotechnical practice, soil stratigraphy is 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 [15]. Another alternative is to identify layering based
on soil behavior classification charts [e.g. 16-19]. 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 [15] 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 [11]. 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). This layering gave a reasonable layer location for unit 3 for BH1. However, the method was unable to identify top of unit 3 in the other three cases, resulting in layer boundaries being significantly off for the other boreholes. 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 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 [15].**

| 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*                                 |                  | *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. 16-19]. 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 ($q_t$), sleeve friction ($f_s$), and pore pressures measured behind the cone shoulder ($u_o$). 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 ($B_q = (u_2 - u_o)/q_n$) where $q_n$ is the net cone resistance ($q_n = q_t - \sigma_v$), $q_t$ is the total cone tip resistance corrected for unequal end areas; $\sigma_v$ is the total vertical stress; $u_2$ the in situ pore pressure.

In this study selected SBT classification charts [16-19] are assessed using the spreadsheet program developed at NPRA by Valsson [20]. These charts were evaluated based on their ability to identify behavioral change around unit 3. Studying the $R_f$ and $B_q$ depth profiles from the borings, both indicated a distinct shift in the curves when entering Unit 3, Figure 5. However, almost none of the SBT charts indicated a behavioral 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. [16] is further looked at in this study. 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 BH5 and BH19, in
Figure 4. For a given CPTu boring data, it is noticed that the distribution of data into the various soil behavior classes is different between the two methods, Figure 4. These classifications are given along with depth profile, for the four borings, in Figure 5.

From Figure 5, it is observed that the SBT chart based on $R_f$ and $q_t$ indicated a layer with behavioral change around unit 3. The chart described the behavior of this layer as “sensitive fine-grained”. It gave a good match for start of unit 3 for BH19. Still, the method is not completely consistent as it also interprets this behavior above unit 3, making it a challenge to precisely identify the start of unit 3, see results of BH1, BH5 and BH13. It is noted that the SBT classification chart by Robertson et al. [16] based on $b_q$ and $q_t$ did not indicate the same behavioral change around unit 3 except for BH19 where it was vague. This does not imply that the $b_q$ behavior 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.

Soil behavior 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. [16] based $q_t$ and $b_q$ (to the left) and $q_t$ and $R_f$ (to the right) for BH5 (top two) and BH19 (bottom two).
Figure 5. Soil layering based on NS-EN ISO (to the left), SBT charts (colored 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 ($q_c$, $f_0$, $u^c$) 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. The next measurement looked at is seismic data from the limited bore holes where SCPTu was carried out. The SCPTu equipment used has two sets of geophones 0.5 m apart and recording of shear wave traces was performed at every 1.5 m depth. The shear wave velocity interpreted from these tests did not show any significant or consistent change when entering unit 3. Therefore, 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 ($R_f$). It was observed that these two derived parameters exhibit shift in the curves when entering Unit 3. 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 BH13 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 BH13 lies 20 m away from the nearest acoustic profile and in a sloping ground (see also Figure 3). Otherwise, the established trends of $B_q$ and $R_f$ in identification of unit 3 is very distinct for BH1, BH5 and BH19 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 can 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.
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