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Use of the free fall cone penetrometer (FF-CPTU) in offshore landslide hazard assessment

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ABSTRACT: Free Fall penetrometer (FF-CPTU) testing can provide significant advantages over conventional CPTU investigation for shallow sub-surface offshore site investigations. Much work has been done on soil characterisation and on determination of the undrained shear strength (s_u) from FF-CPTU testing. However, little data has been published on analysis of FF-CPTU dissipation testing. Here, FF-CPTU data from two Norwegian fjords with evidence of recent landsliding are presented, and the techniques used to analyse and correct the data are described. At Hommelvika, relatively high residual excess pore pressures (15–17 kPa) were found in the vicinity of a large pockmark identified on the fjord bed from multibeam data. At Finneidfjord, the residual excess pore pressures are lower and are in agreement with long-term piezometer data from the area. Reliable estimates of the coefficient of consolidation (c_h) were also be obtained from the FF-CPTU dissipation tests.

1 INTRODUCTION

Near-shore and submarine landslides are hazards along Norwegian fjords and in other similar environments worldwide. One particular issue is the occurrence of excess pore water pressure in relatively thin soil layers that undermines the stability of slopes. This phenomenon has led to a number of significant slope failures, including the well-documented 1996 Finneidfjord landslide (Longva et al. 2003). As the investigation of the seafloor conditions using conventional CPTU or drilling techniques is difficult and expensive, an alternative, less expensive and faster approach for investigating these situations using the free fall piezocone penetrometer (FF-CPTU) is presented herein. As pointed out by Strout & Tjelta (2005) and others, offshore dissipation testing and interpretation of the results are challenging.

The focus of this paper lies therefore on the use of overnight dissipation tests in order to determine the pore pressure regime in specific soil layers. Dissipation test data and the analysis workflow applied from two offshore sites at Finneidfjord and Hommelvika in Norway are examined. The analysis of the data allows for the determination of the excess pore water pressures as well as the coefficient of consolidation. Finally, some implications of the findings for landslide hazard assessment are discussed.

2 INSTRUMENT AND DEPLOYMENT METHOD

Standard CPTU testing is the main method of obtaining *in situ* offshore data. This method requires a suitably equipped and relatively large vessel or drilling platform, and therefore, the method is expensive. Reasonable weather conditions are also generally required. FF-CPTU instruments utilise a more simple gravity-driven deployment style. They can be installed from relatively small vessels by two people. Instrument recovery can be facilitated by a battery powered portable winch.

Many FF-CPTU devices have been developed recently (see Chow & Airey 2013, Chow & Airey 2014). These devices are primarily used to characterise the undrained shear strength of the sediments. However, these devices are also useful to study dissipation of excess pore water pressures and the consolidation characteristics of the soils (Chow et al. 2014). Lucking et al. (2017) describe how the pore pressure response during FF-CPTU

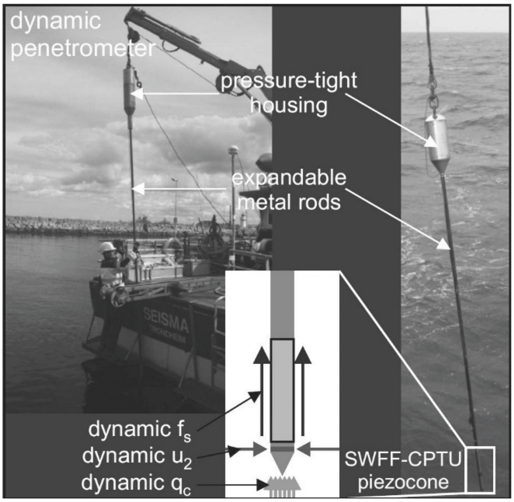

Figure 1. Free-fall penetrometer instrument (modified after Steiner et al. 2013).

penetration can be used to help characterising near-shore sediments.

The FF-CPTU instrument used in this study was developed at MARUM (Center for Marine Environmental Sciences, University of Bremen, Germany), see Figure 1. A full description of the device is given by Stegmann et al. (2006a) and Stegmann et al. (2006b). It is designed to free-fall through the water column, impact the seabed and record penetration data at a high sample rate.

The instrument uses a 15 cm^2 / 10 MPa GEOMIL subtraction piezocone measuring cone resistance (q_c), sleeve friction (f_s), pore pressure behind the tip during penetration (u_2), but also tilt, and *in situ* temperature. It has a modular design and the length can vary between 1.5 m (short mode) and 7.5 m (long mode) by adding 1 m long rods. The length of the probe used in this study was 7.5 m. Depending on the sediment strength, modular weight pieces (15 kg each) can be added in order to achieve deeper penetration (up to 4 × 15 kg-pieces). The weight of the instrument ranges from 45 kg in short mode to a maximum of 170 kg in long mode.

Data logging frequency is variable but is typically set to 40 Hz. Binary data are temporarily stored on a micro flash card and then downloaded to a computer.

3 SITE DESCRIPTIONS

Data from two Norwegian sites at Finneidfjord and Hommelvika are presented here. A short description of each site follows.

3.1 *Finneidfjord*

The 1996 landslide at Finneidfjord and the subsequent investigations and analyses are well described by Longva et al. (2003), Lecomte et al. (2008), Cassidy et al. (2008) and L'Heureux et al. (2012a), amongst others. Steiner et al. (2012) described the use of the FF-CPTU at 38 locations across or in the immediate vicinity of the landslide area to characterize the strength of the soft layers at this site (Figure 2).

Ground conditions in the Finneidfjord area comprise beach deposits (sand and gravel) overlying a thick sequence of clayey silts resting on bedrock (Fig. 3). Significant pockets of very sensitive clay and quick clay were found at several locations along the shoreline and also offshore (Fig. 3).

L'Heureux et al. (2012a) suggest that this landslide initiated within a weak layer in the fjord-ma-

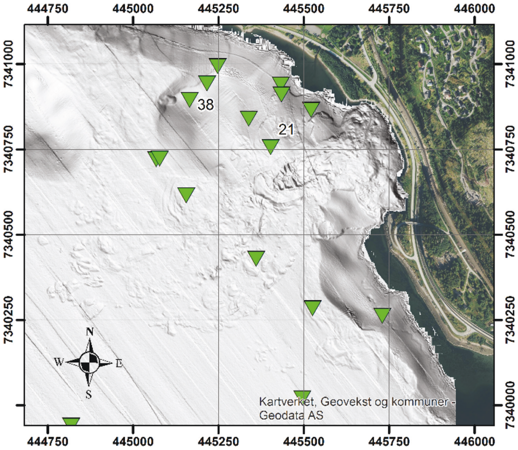

Figure 2. Swath bathymetry image of the Finneidfjord study area showing the location of free-fall penetrometer tests (green triangles) performed in 2010. Piezometers were also installed at FF-CPTU location 21.

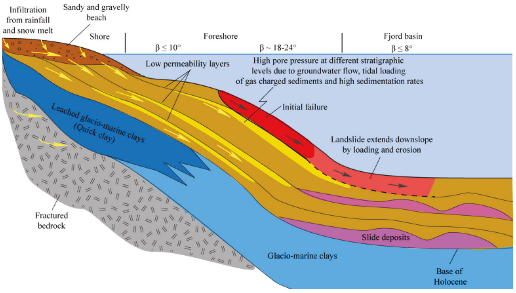

Figure 3. Conceptual stratigraphical model and slope failure mechanism at Finneidfjord (modified after L'Heureux et al. 2012).

rine sediments before developing retrogressively across the shoreline. They explain that, through the integration of results from sediment cores, free-fall cone penetrometer tests and high-resolution 3D seismic data, the slide-prone layer is a regional bed likely sourced from clay-slide activity in the catchment of the fjord. The sediments in this regional layer are softer and more sensitive than the typical fjord-marine deposits, which explain their role in slope instability.

3.2 *Hommelvika*

The bay of Hommelvika is located approximately 20 km northeast of Trondheim, Norway. Ground conditions in the Hommelvika area comprise a complex distribution of sandy silts overlying silty clay. The clays are generally of medium sensitivity. The FF-CPTU work at Hommelvika was designed to investigate large pockmarks (Figure 4). The purpose of the FF-CPTU testing was to characterise the nature of the materials and their undrained shear strength. In addition, the possible presence of excess pore pressure inside and close to the large pockmarks was of interest (Figure 4). The pockmarks are up to 75 m in diameter and 5 m deep. They can be an indication of groundwater seepage.

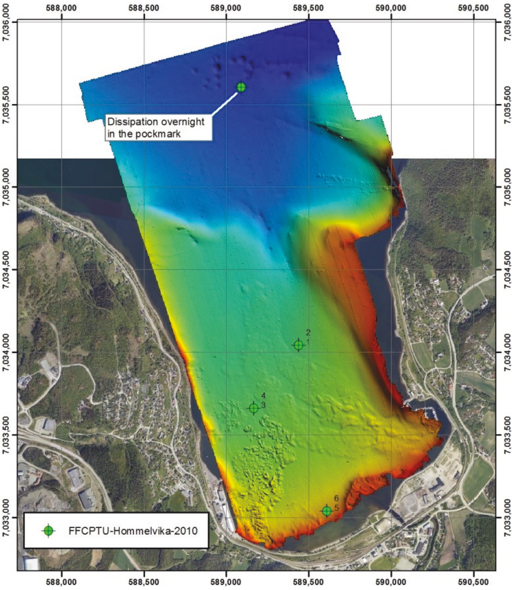

Figure 4. Swath bathymetry image of the Hommelvika study area showing the location of free-fall penetrometer tests performed in 2010. Landslide debris and large pockmarks are also observed on the fjord bottom.

The excess pressure likely originates from groundwater infiltration in the near-shore sediments due to the significant topographic gradients in the region. Similar processes and pockmarks are often observed in other lakes and fjords in Norway e.g. Lake Botnen at Rissa; L'Heureux et al. (2012b).

4 DATA PROCESSING

4.1 *Strategies for FF-CPTU tests*

Generally, three options are available for FF-CPTU tests. Type A testing aims at a high-resolution vertical record (1 kHz logging frequency) of the sediment properties. The FF-CPTU instrument is lowered at 1.0 to 2.0 m/s winch speed to a level 10 m to 15 m above the seafloor. It is then released in free–fall mode until the probe impacts the seafloor and dynamically decelerates until its terminal depth is reached. The instrument is recovered immediately after the FF-CPTU probe comes to a complete halt. Due to the short time length of the test, no dissipation data for pore pressure is recorded.

Type B testing is initially similar to Type A (same test parameters). However, it aims at the recording the absolute pore pressure evolution once the FF-CPTU instrument is embedded in the sediment. Pore pressure dissipation is usually recorded for 20 minutes to 25 minutes.

Type C testing focuses on the logging of the absolute pore pressure evolution overnight (pore pressure dissipation for 12 hours to 15 hours) using a recording frequency of 10 Hz. The deployment is basically similar to Types A and B. Only pore pressure is recorded. As of yet, the system does not allow recording pore pressure response and other parameters for extended periods of time.

4.2 *Examples of Type B dissipation tests*

Some examples of Type B, short term dissipation tests, for the Hommelvika site are shown on Figure 5. The location of the tests is shown on Figure 4.

On impact with the fjordbed, negative excess pore pressures develop. These reach a minimum value at the end of the FF-CPTU penetration and then slowly rise to reach a maximum after a while. Seifert et al. (2008) classify this pattern of pore pressure behaviour as a "Type B1" signal and suggest the development of the negative excess pore pressure is due to a combination of factors, including the dilatory response of the soil due to some silt and sand content and also the presence of gas in the sediments. The tests were of insufficient

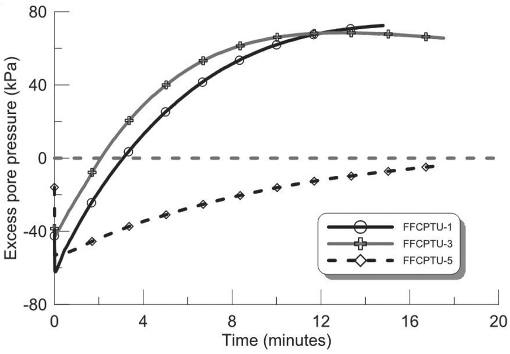

Figure 5. Short term dissipation tests for Hommelvika.

length for any subsequent dissipation of the excess pore pressure to be observed. Thus, for these tests, it is not possible to obtain the *in situ* excess pore water pressure.

Tests 1 and 3, located towards the center of the bay, show very similar results. Test 5, close to the edge of the bay, shows a much slower recovery of pore pressure.

4.3 *Long term Type C dissipation tests*

Results from three Type C tests at Finneidfjord and one at Hommelvika are also available. Due to the overnight duration of these tests, the data require corrections to take into account tidal effects and atmospheric pressure variations. These corrections can be either positive or negative.

Values for the absolute pore pressure were recorded by the instrument every tenth of a second over the 13 to 19 hour period during the long-term dissipation testing at the three locations. Due to the large amount of data recorded during testing, values of absolute pore pressure corresponding to 10 minute intervals were selected for plotting. As for the Type B tests, the pore pressure initially decreases as expected and then reaches a maximum before dissipating slightly and then rises again. The subsequent rise in pore pressure after the initial decline confirms that correction of the data is required.

The correction required to be applied to the data due to tidal effects is calculated as follows:

$$p_{tide} = \rho_{sw} g h \tag{1}$$

where:

p_{tide} = correction to measured pore pressure reading

ρ_{sw} = density of seawater = 1030 kg/m^3

g = acceleration due to gravity = 9.81 m/s^2

h = mean tide level during test—actual tidal observation (referenced to "zero" datum)

A similar approach was adopted for corrections in atmospheric pressure variations (p_{air}). The standard reference value of atmospheric pressure (taken to equal 101.325 kPa) was subtracted from the measured value of the air pressure (corresponding to the same time as the pore pressure value under study).

Finally the corrected pore pressure value is determined as follows:

$$u_{2,corrected} = u_{2,measured} + p_{tide} + p_{air} \tag{2}$$

Excess pore pressure (Δu) is obtained from:

$$\Delta u = u_{2,corrected} - u_0 \tag{3}$$

where:

u_0 = *in situ* hydrostatic pore water pressure corresponding to mean tide level.

In any case, none of the test results were corrected for fluid dynamic effects such as Bernoulli.

5 RESULTS AND DISCUSSION

5.1 *Excess pore pressures (EPP)*

The results of the three long term dissipation tests, with the results corrected as described above, are shown on Figure 6.

The residual excess pore pressure values are:

- ○ Hommelvika FFCPTU-7 = 15–17 kPa
- ○ Finneidfjord FFCPTU-21 = 2–4 kPa
- ○ Finneidfjord FFCPTU-38 = 5–7 kPa

5.2 *Comparison with piezometers*

In order to assess the accuracy of these calculated *in situ* values, we compare the results with long-

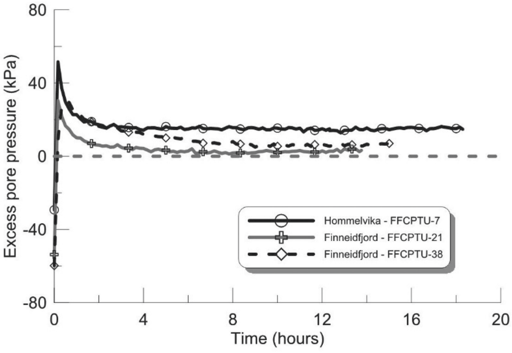

Figure 6. Long term dissipation tests at Hommelvika and Finneidfjord.

term piezometer tests carried out at a nearby location in Finneidfjord (red circle; Fig. 2). Three set of piezometer data are available for Finneidfjord. These instruments were connected to logging stations located onshore. Data is logged hourly and transmitted once per day.

Figure 7 shows an example of the data from PZ2.3. The average *in situ* excess pore pressure in July 2013 is around 4 kPa and varies throughout the year [figure only shows 1 month] between 2–5 kPa. Thus, the piezometer results agree very well with the data from the FF–CPTU tests. Figure 7 also presents information about temperature, rainfall, tidal variation and total pressure variation during the measured time period. The excess pore pressure ratio R_u ($R_u = \Delta u/\gamma_{tot}\cdot z$ where γ_{tot} is the total unit weight of the soil and z the depth below seafloor) is also shown and ranges from 0.19–0.26.

5.3 *Comparison with seabed features*

At Hommelvika, relatively high excess pore pressures occur in the vicinity of a large pockmark (Figure 4). The presence of excess pore pressure inside the pockmark could be an indication of groundwater seepage as a key part of its formation. The excess pressure from the groundwater seepage may be sourced from high pore pressure gradients in the near-shore sediments as is the case with pockmarks in Lake Botnen in Rissa, Norway (L'Heureux et al. 2012b). Comparisons with piezometers located along the shoreline at Hommelvika confirm that significant hydraulic gradients exist.

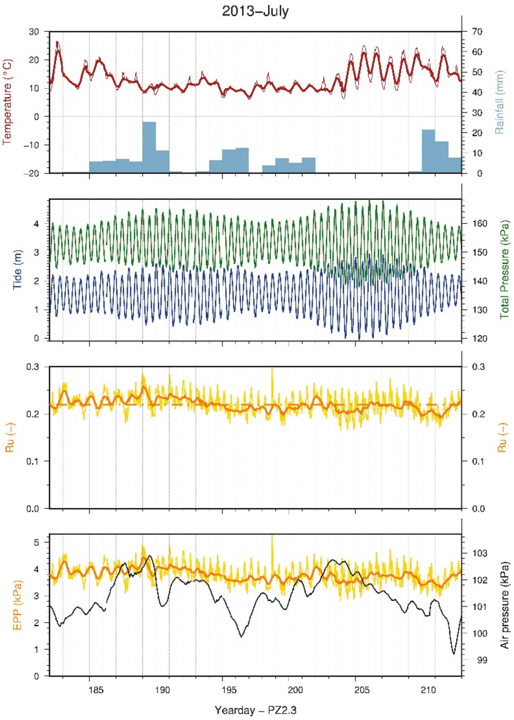

Figure 7. Long term interpretation of piezometer data for a selected period (July 2013) at the Finneidfjord site. EPP: residual excess pore pressure.

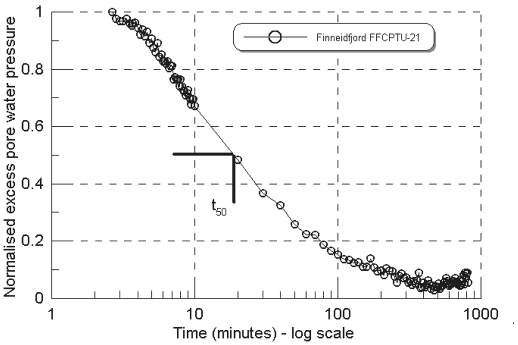

Figure 8. Example of calculation of c_h from long-term dissipation test data.

5.4 *Coefficient of consolidation*

Long-term dissipation test data can also be used to determine the coefficient of consolidation c_h. Several methods are available for performing these calculations. In the example shown on Figure 8 (Finneidfjord test FF-CPTU-21) the classic technique outlined by Teh & Houlsby (1991) is used to determine c_h by obtaining the time for 50% consolidation of excess pore pressure (t_{50}) from the test data. The following values of c_h were determined:

○ Hommelvika FF-CPTU-7 = 47 m^2/yr.
○ Finneidfjord FF-CPTU-21 = 60 m^2/yr
○ Finneidfjord FF-CPTU-38 = 10 m^2/yr.

6 CONCLUSIONS AND IMPLICATIONS

Free-fall penetrometer tests provide a valuable and time-efficient method for shallow offshore geotechnical site investigation. One particular issue in such environment is the potential occurrence of excess pore water pressures that—if present—would undermine the stability of slopes. Using a simple analysis workflow including, amongst other things, corrections for tidal effects and atmospheric pressure variations, results obtained from two study sites at Hommelvika and Finneidfjord in Norway compared well with piezometer data and morphological seafloor features. At Hommelvika, relatively high residual excess pore pressures

(15–17 kPa) were found in the vicinity of a large pockmark. At Finneidfjord, the excess pore pressures are lower and are in agreement with long-term piezometer data from the area. The analysis of the data also allows determining the coefficient of consolidation in the clays.

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REFERENCES

Cassidy, M.J, Uzielli, M., Lacasse, S. 2008. Probability risk assessment of landslides: A case study at Finneidfjord. Canadian Geotechnical Journal 45 (9):1250 1267.

Chow, S.H. & Airey, D.W. 2013. Soil strength characterisation using free-falling penetrometers. Géotechnique 63 (13):1131–1143.

Chow, S.H. & Airey, D.W. 2014. Free-falling penetrometers: a laboratory investigation in clay. Journal of Geotechnical and Geoenvironmental Engineering ASCE 140 (1):201–214.

Chow, S.H., O'Loughlin, C.D., Randolph, M. 2014. Soil strength estimation and pore pressure dissipation for free-fall piezocone in soft clay. Géotechnique 64 (10):817–827.

L'Heureux, J.S., Longva, O., Steiner, A., Hansen, L., Vardy, M.E., Vanneste, M., Haflidason, H., Brendryen, J., Kvalstad, T.J., Forsberg, C.F., Chand, S., Kopf, A. 2012a. Identification of weak layers and their role for the stability of slopes at Finneidfjord, northern Norway. In: Y. Yamada et al. (eds). Submarine Mass Movements and Their Consequences, Advances in Natural and Technological Hazards Research, 29, Springer, Dordrecht (The Netherlands). 321–330.

L'Heureux, J.S., Eilertsen, R.S., Glimstad, S., Issler, D., Solberg, I.-L., Harbitz, C.B. 2012b. The 1978 quick clay landslide at Rissa, mid-Norway: subaqueous morphology and tsunami simulations. In: Y. Yamada et al. (eds). Submarine Mass Movements and Their Consequences, Advances in Natural and Technological Hazards Research, 29, Springer, Dordrecht (The Netherlands). 507–516.

Lecomte, I., Bano, M., Hamran, S.E., Dalsegg, E., Nielsen, K.M. 2008. Mapping quick clay sites for geohazard assessment: the Finneidfjord case study, Norway. Paper presented at the Near Surface 2008–14th European Meeting of Environmental and Engineering Geophysics Kraków, Poland, September 2008.

Longva, O., Janbu, N., Blikra, L.H., Bøe, R. 2003. The 1996 Finneidfjord slide: seafloor dynamics. In *Submarine mass movements and their consequences* (pp. 531–538). Springer, Dordrecht.

Lucking, G., Stark, N., Lippmann, T., Smyth, S. 2017. Variability of in situ sediment strength and pore pressure behavior of tidal estuary surface sediments. Geo-Marine Letters 37:441–456. doi:10.1007/s00367-017-0494-6.

Seifert, A., Stegmann, S., Mörz, T., Lange, M., Wever, T., Kopf, A. 2008. In situ pore-pressure evolution during dynamic CPT measurements in soft sediments of the western Baltic Sea. Geo-Marine Letters (2008) 28:213–227. doi:10.1007/s00367-008-0102-x

Stegmann, S., Mörz, T., Kopf, A. 2006a Initial results of a new free fall-cone penetrometer (FF-CPT) for geotechnical in situ characterisation of soft marine sedimentsVo l. 86, No. 3, pp. 199–208. Norsk Geologisk Tidskrift (Norwegian Journal of Geology) 86 (3):199–208.

Stegmann, S., Villinger, H., Kopf, A. 2006b. Design of a modular, marine free-fall cone penetrometer. Sea Technology 47 (2):27–33.

Steiner, A., Kopf, A., L'Heureux, J.S., Kreiter, S., Stegmann, S., Hafliadason, H., Moerz, T. 2013. *In situ* dynamic piezocone penetrometer tests in natural clayey soils – a reappraisal of strain-rate corrections. Canadian Geotechnical Journal 51:272–288.

Steiner, A., L'Heureux, J.S., Kopf, A., Vanneste, M., Longva, O., Lange, M., Haflidason, H. 2012. An in-situ free-fall piezocone penetrometer for characterizing soft and sensitive clays at Finneidfjord (Northern Norway): Free-fall CPTU at Finneidfjord. In: *Submarine Mass Movements and Their Consequences, Advances in Natural and Technological Hazards Research*, 29, Spinger, Dordrecht (The Netherlands). pp. 99–109. 978-94-007-2161-6

Strout, J.M. & Tjelta, T.I. 2005. *In situ* pore pressures: What is their significance and how can they be reliably measured? Marine and Petroleum Geology 22 (1–2):275–285.

The, C.I. & Houlsby, G.T. 1991. Analytical study of the cone penetration test in clay. Géotechnique 41 (1):17–34.

Vanneste, M., Longva, O., L'Heureux, J.S., Vardy, M.E., Morgan, E., Forsberg, C.F., Kvalstad, T.J., Strout, J.M., Brendryen, J., Hafliadason, H., Lecomte, I., Steiner, A., Kopf, A., Mörz, T., Kreiter, S. 2013. Finneidfjord, a field laboratory for integrated submarine slope stability assessments and characterization of landslide-prone sediments: a review. Paper presented at the Offshore Technology Conference (OTC).