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Geohazard assessment of the Yggdrasil Power from Shore electrification project in Western Norway

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ABSTRACT: The Yggdrasil Power from Shore project aims to electrify the Yggdrasil field in the North Sea by 2027. This study highlights the research on submarine landslides conducted as part of the geohazard risk mitigation of geohazards for the 80 km inshore power cable. The resulting failure frequency of the cable was based on a quantitative assessment of the natural and manmade trigger mechanisms and is estimated based on a combination of multi-disciplinary desktop-studies, advanced earthquake analyses (e.g. FE program PLAXIS), field observations, geotechnical and geophysical ground investigations and advanced laboratory investigations. The mapping assessment identified evidence of a total of 184 prior submarine landslides along the proposed cable routing, cataloguing their geometric and morphological slide characteristics. Furthermore, a post-failure analysis was performed on the fjord flanks to estimate the slide movement energy, erosion depth and the reconsolidation ability of the soil in order to plan a repairing strategy in areas with disturbed soil. The correlation between submarine slides and earthquake activity has been assessed based on site-specific seismic analysis (PSHA) carried out as well as age dating of soil samples to estimate the expected historical and future recurrence interval of slide events.

Keywords: Geohazards; Post-failure analysis; Risk of failure; Submarine Slide Mapping; Slope Stability, Seismic geophysical investigation, offshore soil sampling and cone penetration tests

1 BACKGROUND

Today, there are 16 fields that have adopted or decided to adopt power from shore from Western Norway in the North Sea. This corresponds to about half of Norway's petroleum production (Sokkeldirektoratet, 2020). Electrification of the continental shelf involves replacing the use of gas in gas turbines on the platforms with electricity supplied via cables from the mainland (NVE, 2023).

The Yggdrasil Power from Shore (PfS) electrification project, is aimed at electrifying the Yggdrasil field located in the North Sea by 2027. As part of the project, a 260-kilometer power cable will be connected to land in Western Norway and extend to the Yggdrasil area between the Alvheim and Oseberg fields in the North Sea. Several studies have been conducted to identify relevant failure mechanisms and associated risks of cable breakage, with the goal of finding the best-suited cable route from the connection point at the innermost part through the 80-kilometer stretch through the fjords and out to the open sea. The landscape in the area consists of narrow fjord corridors with adjacent steep mountains and slopes, which also form steep underwater flanks. Geophysical surveys have identified several historical underwater landslide events in the area. Geotechnical campaigns conducted along the cable route and the flanks indicate accumulated deposits of soil with low shear strength. The existing terrain conditions and the presence of soft, sensitive materials are considered to represent a high probability of future landslide events in the area, posing a subsequent risk of cable breakage. Therefore, evaluating underwater geohazards and the expected impact on the power cable is critical for assessing the optimal cable route and protection philosophy.

2 INTRODUCTION ON SUBMARINE GEOHAZARDS

In contrast to landslides on land, the size of underwater landslides can develop in relation to the amount of shear strength lost when a slope fails. A rapid release of pore water can lead to a state of underconsolidation and a resulting low static shear strength, causing rapid failure development. The dynamics of underwater landslides make it possible for large volumes of sediment to be mobilized and travel long distances, historically reported to reach up to 20,000 km³ and increasing 140 km (Clare et al. 2019).

For subsea installations such as electrical cables, it is not sufficient to only assess the stability conditions along the cable route; it is also important to consider the impact of potential landslides from adjacent slopes where underwater landslides can be triggered, resulting in damage or breakage of the subsea cable. Submarine landslides can be triggered by various factors, including rapid sediment deposition, earthquakes, large storm waves, and the buildup of pore pressure (Clare et al. 2019).

The triggering mechanisms for such slope failures can be divided into human-induced and natural factors. Natural triggering mechanisms include overland landslides and rockfalls within reach of the fjord, which may discharge into the fjord. In this way, an underwater landslide can develop on the seabed. Earthquakes represent the most significant triggering factor for naturally induced landslides in the area under investigation. An earthquake can reduce stability due to seismic loads applied to the soil, in addition to a reduction in shear strength due to cyclic loading. Human-triggered mechanisms have historically caused numerous subaerial and submarine landslides along Norwegian fjords, due to construction work near the shoreline, blasting, excavations, fill operations, anchoring of fish farms, etc. (Clare et al. 2019).

3 FIELD AND LABORATORY INVESTIGATIONS

3.1 Ground conditions

The geohazard assessment that was part of the Yggdrasil PfS project started in 2021 and was finished in 2024. Soil investigation campaigns in the fjord include detailed bathymetry and geophysical surveys of the cable corridor. Addition geotechnical soil sampling, CPTUs and supplementary gravity core sampling have been performed selected flanks in the basin and on the flanks. Geophysical sub bottom profiler (SBP) data allows high resolution imaging of the subsurface up to 80 m depth below seafloor. The inspected flanks are generally exposed bedrock in slope angles between 25 – 40 degrees. Remaining sediments was detected in slopes increasing 10 degrees. CPTUs and piston core soil samples down to a maximum of 30 m below seabed were obtained. Laboratory testing indicates a pattern of mainly soft, homogeneous clay and organic gyttja characterized as very soft, high plasticity and low strength.

3.1.1 Age dating of submarine geohazards along the Yggdrasil PfS cable route

An age model for the landslide history was developed by incorporating C-14 age dating and derived sedimentation rates based on 15 selected samples. A combination of index testing and multi-sensor core logging (MSCL) are basis for the litho-stratigraphical analyses, including sample disturbance and soil layering. The main findings from the age dating analysis show that the majority of the slides have developed in the last 4000 years before present, as can be seen in Figure 3-1. The sedimentation rate in Holocene was less than 0.5 mm/year.

Figure 3-1: Age-dating results performed on samples along the Yggdrasil cable route. The samples have been obtained in natural sedimented soil on top of identified slide deposits. The uncertainty in the age dating measures is represented by a maximum age (blue lines) and minimum age (orange lines).

4 METHODOLOGY AND OUTCOME FROM THE GEOHAZARD ASSESSMENT

Desktop studies were initially conducted to establish an understanding of the stability conditions in the fjord and relevant triggering mechanisms of potential geohazards. These studies investigate subaerial geohazards, submarine geohazards, earthquakes and the stability condition of selected flanks. The results are basis for an overall division of the fjord into risk-zones with corresponding low, medium and high risk for future geohazards that could affect the cable route.

4.1.1 One Dimensional Slope Stability

The occurrence of earthquakes and their impact on slope stability based on the resulting seismic effects have been assessed based on response curves derived from 26 geographical points along the cable route. The earthquake spectra vary in magnitude due to different distances from faults. An overview of historical earthquakes in the area are shown in Figure 4-1. The reduction in slope stability was analysed in the assessment, considering the reduction in stability was obtained as a function of return period and slope inclination, where both slope failures during the earthquake event and post-failure after the seismic event.

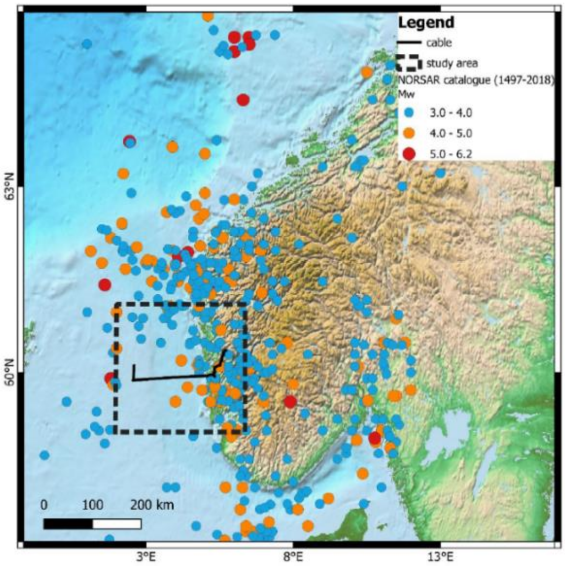

Figure 4-1: An overview of historical earthquakes in the area. The cable route is marked with a black, dashed outline. Relevant earthquakes have magnitudes ranging from 3.0 to 5.0.

Figure 4-2 shows the relationship between the factor of safety and slope inclination, where the different curves represent different seismic conditions, ranging from static condition to a 10,000-year earthquake. The analyses are based on a low estimate shear strength profile, with a critical slope inclination ranging from 0 to 18 degrees. The results show that earthquakes with return period of 100 years have an insignificant effect on the factor of safety related to the slope stability.

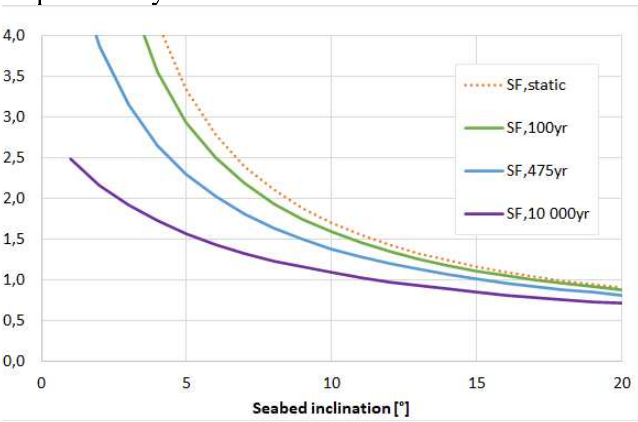

Figure 4-2: Factor of safety as function of seabed inclination for 100-, 475- and 10.000-year earthquakes.

An overall impression of the stability condition in the fjord was gained by performing one-dimensional stability evaluations. The calculations are based on equation (I) for static condition and (II) for dynamic condition. The inputs are derived from performed soil investigations in addition to quasi-static earthquake loads (k) from Uniform Hazard Spectra (UHS) for 100 and 10.000 years.

$$FS_{static} = \frac{C_u}{(p_0' * cos\beta * sin\beta)} \qquad \text{(I)}$$

Undrained shear strength (c_u/p_0'): 0.29 ($\sim Cu_{NC-clay}$)

$$FS_{dynamic} = \frac{C_u}{(p_0' * cos\beta * sin\beta) + (p_0 * k_h * \cos^2\beta)} \qquad \text{(II)}$$

The quasi-static earthquake factor (k_h) with 100 and 1000 years return period is 0,004 and 0,0004 respectively. The vertical stress can be calculated as p_0=3* p'$_0$, where the ratio between the total and effective unit weight is 15 kPa/5kPa=3.

The results from the one-dimensional stability analysis show that the majority of the flanks have a FoS which is below 1.0 or slightly above 1.0, illustrated by the red areas in Figure 4-3, however, this preliminary approach shall be considered with caution since most of the steep slopes are belived to be exposed bedrock.

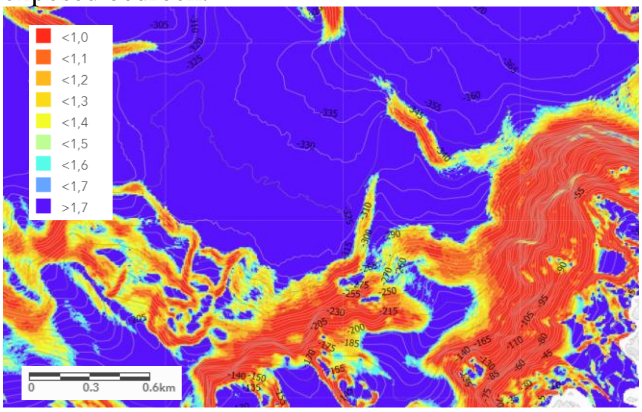

Figure 4-3: Factor of safety plot indicating the in-situ stability condition of the slopes in the basin for return period of 100 years. The elevation lines indicate the bathymetry in meters below sea level.

4.1.2 Subaerial geohazard assessment

The background for the study of subaerial geohazards is that this is considered a significant triggering mechanism for underwater landslides due to the steep terrain and the exposed cliffs that form the landscape around the fjords. The overland landslide hazard assessment includes the registration of planned activities in the shoreline, as well as the identification of unstable steep slopes and cliffs. It is expected that any landslide or rockfall reaching the fjord could propagate further along the slopes and/or contribute to triggering underwater landslides that may impact the subsea cable.

In this study, overland geohazards include landslide mechanisms consisting of soil slides, rockslides, rockfalls, and slush avalanches. Additionally, a numerical analysis of runout distances for relevant landslide terrain in the area has been performed, where masses could move towards the fjord. These hazard zones were further investigated in the field by geologists using drones and field mapping. In this way, the general hazard zones were further refined in extent based on fracture patterns, faults, and deposits from previous landslides. Each of the resulting hazard zones were mapped based on the guidelines from the Norwegian Water Resources and

Energy Directorate (NVE) for hazard mapping (NVE, 2022) and the Technical Regulations (TEK17) Chapter 7 (DIBK, 2017). The annual landslide recurrence intervals of some specific areas on the fjord flanks vary from 1/100 to 1/3000 years based on the study of previous hazard events and numerical analysis of rockfall run-out distances heading towards the fjord.

The overland mapping of geohazards also includes the identification of relevant planned activities in the shoreline. A total of 47 ongoing or planned activities in the shoreline along the fjords were mapped, including fish farms, boathouses, and industrial facilities.

4.1.3 Submarine geohazard assessment

The mapping assessment of historical landslide activity provides an overarching view of the frequency and characteristics of landslides in the 80 km long fjord section. The mapping assessment of previous geohazards focuses on the naturally induced geohazards, including submarine landslides on the cable route and fjord flanks. Based on morphological characteristics, landslides can be divided into slides, topples, spreads, falls and flows (Clare et al. 2019). For this study, the implemented landslide types are slump, flow, rockfall, combined mud- and rock-fall, flow with out-runners and turbidity flow. The mapping of slide types is based on inclination of the release and deposition areas, internal structure and layering, runout distance, volume of the landslide etc. These geometric and morphological properties are assessed for each of the identified historical landslides where the data allows for it.

The seismic sub-bottom profiles (e.g. the profile shown in Figure 4-4) have formed the basis for detailed mapping and extent of landslide deposits with characteristics such as slide geometry, runout distance, erosion depth, thickness of the landslide, direction of movement, overlay, and internal structure of the deposits and surrounding naturally deposited masses on the seabed. The identified slide characteristics of previous landslides are basis for understanding of future submarine slides.

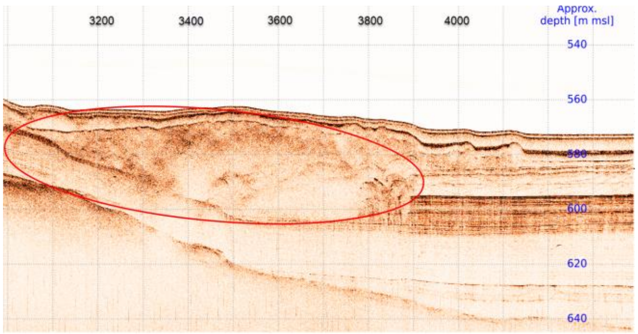

Figure 4-4: Sub-bottom profile indicating one identified slide deposit. This case shows a slide with a thickness of 30 m and a cover of 6 m on top. The run-out length is approx. 300 m.

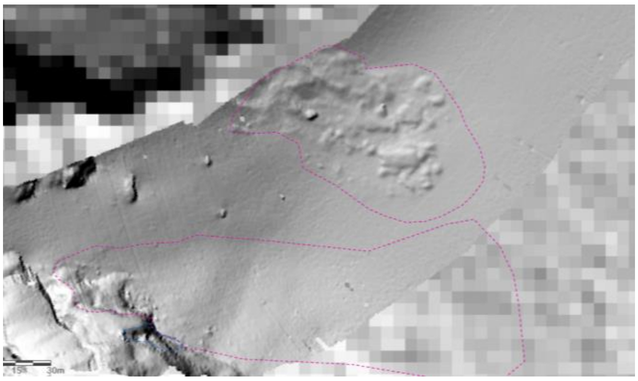

Figure 4-5: Hillshade map of the seabed showing two examples of slide deposits. The slide deposits are typically covered by natural deposits on top, making the slides less distinct than for this case.

The mapping has identified 184 submarine slides. It is probable that more slides have occurred, not identified herein, in areas with limited data and resolution. The study shows a distinct difference in slide dynamics between the different fjord sections. The majority of the identified slides are located in the inner part of the fjord, triggered by subaerial activities. These slides show a pattern of distinct and small slides with origin of the last 2000 years. Landslides mapped on the outer part of the fjord are larger in extent and considered to be triggered by earthquake activity. In the outer part of the fjord, the typical slide events are increasing in size and thickness, typically between 250 – 1200 width and 20 – 40 m thick. The majority of the identified slide events are considered to have occurred in the last 4000 years, with a sediment cover less than 2 m and an assumed sedimentation rate less than 0.5 mm/year. A high sedimentation rate is considered to correlate to a higher frequency of slope failure in the same flanks. The obtained sedimentation rate was less than 0.5 mm/year in Holocene, which gives a very low expected frequency and a high recurrence time of significant slope failures at the same flanks. Following, it is expected that naturally induced landslide events in the studied fjords are likely to occur in areas with accumulated sediments. The Yggdrasil NPRA finding can be seen in comparison with the Bjørnafjorden NPRA study of historical earthquake activity with a resulting recurrence interval of approx. 500 years between major earthquake incidents (NPRA, 2017).

4.2 Detailed assessment of geohazards along the cable routing

4.2.1 Static and dynamic 2D slope stability analyses using PLAXIS

Based on supplementary soil investigations in selected slope profiles on fjord flanks, in-situ stability conditions have been assessed using 2D calculations in PLAXIS. The 1D stability analysis (e.g. Figure 4-3) is high-level calculations based on typical soil conditions and 5 m resolution slope maps. For the 2D analysis, the input is site specific for each profile, based on representative ground investigations and topography from sub-bottom profile along the slope. The calculations were performed for both static and dynamic conditions to evaluate the effects of seismic loads from earthquakes with a recurrence interval of 1/100 and 1/10,000 years. The slopes are considered to fail at approximately 3% strain. The calculations show that all slopes remain stable under static conditions, with a safety factor ranging between 1.09 to 1.90. When seismic loads are applied, the stability of the slopes decreases between 1.05 to 1.80 for an earthquake with a 1/100 recurrence interval. For a 1/10,000-year earthquake, two out of three slopes fail.

4.2.2 Post-failure analyses

As part of the geohazard study, slope stability and post-failure analyses are performed on 2D sub-bottom profiles to quantify the safety factor of selected flanks in a static and in a dynamic condition (earthquake) and estimating the impact loads and erosion depth on the cable in case of a submarine geohazard occurs. The results have been used as basis for optimalization of the cable route, avoiding areas with higher risk for geohazards as well as input to cable designer for protection philosophy. Key results shown in Figure 4-7 indicate landslide loads ranging from 60 to 300 kPa and erosion depths between 0.2 and 7.0 meters at the bottom of the slopes. Figure 4-6 illustrates the position of the landslide mass on the seabed at t = 0 sec and t = 250 sec.

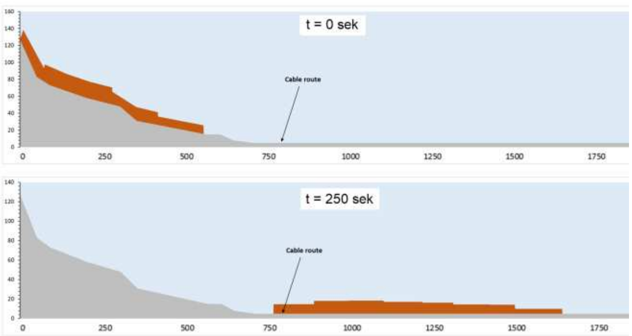

Figure 4-6: Illustration of the slide event from time t=0 sec to time t = 250 sec. The latter corresponds to the last step in the iteration of the post-failure event. Orange area corresponds to slide masses.

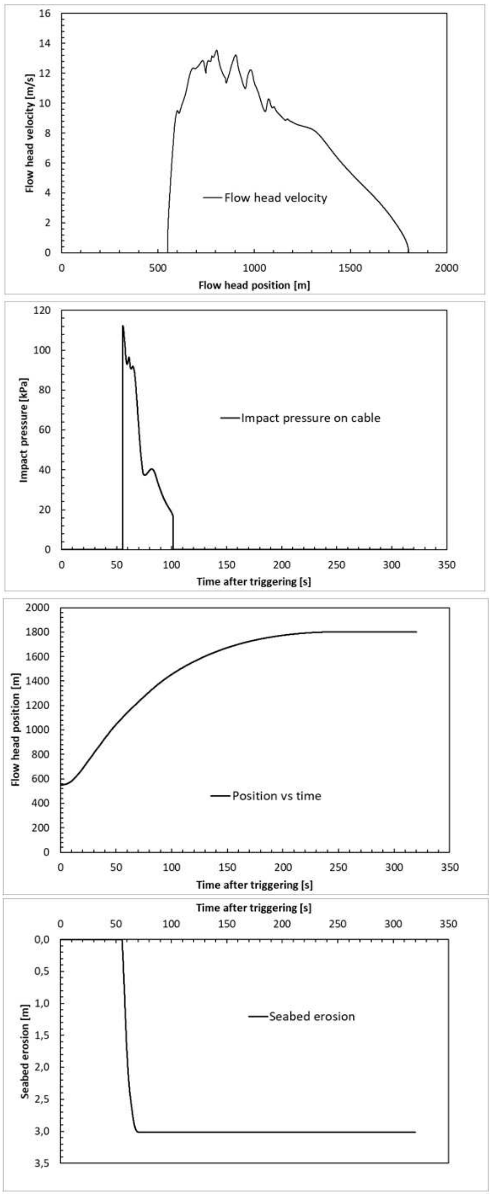

Figure 4-7: Post failure results showing the flow head velocity and position with time, impact pressure and seabed erosion depth. The basis of the seabed erosion assessment is presented in Sørlie et al. (2024). For the impact pressure methodology, see Sørlie et al. (2023).

5 RISK ASSESSMENT RELATED TO FUTURE GEOHAZARDS

The geohazard risk along the proposed Yggdrasil PfS cable route includes mapping of previous submarine landslides, slope stability assessments of particular flanks across the cable route, detailed age dating of the previous landslide deposits and studies of potential trigger mechanisms of submarine geohazards. The investigated trigger mechanisms for submarine slides includes earthquake activity, human activity in the coastline and subaerial slides. The risk of future slides is defined as low, moderate, and high risk of cable failure. Site-specific conditions were taken into account when deciding the risk category, including topographical conditions, type of subaerial hazard, normalized runout-distance and presence/ thickness of accumulated sediments on the flanks.

The majority (58 %) of the investigated sub-bottom profiles is associated with moderate to high risk of future slides affecting the cable routing. Based on sediments remaining on the flanks of the inner fjord, these exist on critical slopes and are possible source areas for future landslide activity. It should be noted that the high-risk profiles are correlating to specific areas and do not represent the stability condition in the entire fjord. There are significant trends in terms of risk level in the different fjord sections, due to varying thickness of remaining sediments, distance to the cable and slope angle. The remaining 42 % of the assessed sub-bottom profiles shows low risk of future slides, including areas with steep flanks increasing 30 degrees with no or limited thickness of sediments.

6 SUMMARY AND CONCLUSION

The geohazard assessment that was part of the Yggdrasil PfS project started in 2021 and was finished in 2024. The projected was divided into two phases, the desktop studies and the detailed studies. The desktop studies were based on seismic data and high-resolution bathymetry in the cable corridor, in addition to CPTUs and soil samples along the suggested cable routing. The introductory work included PSHA-analysis followed by site-response analysis. Further, relevant triggering mechanisms of future slides including subaerial geohazard mapping, zoning activity and mapping of previous submarine slides were identified. Based on these studies, the project was able to highlight the focus areas for further investigations, associated with high risk of future geohazards. The detailed geohazard assessment was based on site-specific soil sampling, age dating, CPTUs and seismic data in the cable corridor and on the flanks. Based on slope stability analysis and post-failure calculations, it was possible to estimate the expected impact of a future submarine landslide in the area and perform a rerouting to minimize the risk.

The risk assessment of future slides is divided into subaerial slide induced geohazards, earthquake induced geohazards and human induced geohazards. The relevant triggering mechanisms for submarine landslides have been found to be seismic activity, human activities in the coastal zone and onshore landslides, including rockfalls and debris flows. Earthquakes of sufficient magnitude to trigger landslides are expected to have a frequency of 1 in 300 for this specific case. Stability calculations indicate that 100-year return period earthquakes do not have a significant effect on slope stability.

Previous landslide events indicate slides of various types throughout the fjord corridors, where the landslides appear to have longer runout distances and larger volumes in the widest parts of the fjord. The landslides in the outer areas are believed to be triggered by seismic activity, while landslide deposits in the inner fjords are thought to be more frequently triggered by onshore activities such as rockslides, mudslides, and human-induced landslides. Based on the accumulation of loose materials on relatively steep slopes, there is a risk of future landslide activity in some areas.

The mapping of previous submarine landslides gives a picture of past activity in different parts of the fjord sections, in addition to characteristics like size, erosion depth and runout distances. The correlation between submarine slides and earthquake activity has been assessed. When linked to the identified slide characteristics, the PSHA study gives evidence of possible triggering mechanisms. The age dating results indicate potential recurrence intervals for future landslides (e.g. <4000 years) providing input to potential cable routing, protection philosophy and repair strategy of the Yggdrasil cable route.

AUTHOR CONTRIBUTION STATEMENT

Ingrid Liplass: Formal Analysis, Methodology, Writing- Original draft. **Erik Sørlie**.: Supervision, Conceptualization, Methodology, Writing – review & editing. **Robert Bendzovski**: Project administration, Supervision, Methodology, Writing – review & editing. **Angel L. A. Martin**: Supervision, Funding acquisition, Methodology, Writing- Reviewing and Editing. **David Brooks**: Funding acquisition.

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