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Geohazard assessment for a submarine cable

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ABSTRACT: This paper describes a geohazard study for a submarine cable passing through fjords with challenging soil conditions and highly variable bathymetry. The main geohazards evaluated included slope stability along the cable corridor and rockfall triggered by earthquakes. One-dimensional static, pseudo-static and displacement analyses along the cable corridor were performed to identify critical locations. For the identified critical zones, static and pseudo-static 2D slope stability analyses using a finite element program and an advanced constitutive model to account for soil anisotropy were conducted. Mitigation measures suggested for slopes with low static factors of safety included rock dumping, trenching, and micro-routing. For low probability earthquake events, contingency planning for rapid inspection and repair post-event was recommended. For the submarine rockfall hazard assessment, runout distances of single blocks were estimated using physics-based analytical solutions. A sensitivity study was performed on key parameters to assess uncertainty. The results showed that the probability for rockfalls to reach the power cable is high for two of the studied locations. However, there were no clear indications of deposited rockfall blocks at the two critical locations. Therefore, the overall likelihood of rockfall impacting the cable is low, given the low probability of rockfall initiation. This assessment ensures the safe and reliable design and installation of a subsea cable, mitigating potential geotechnical risks and informing necessary mitigation measures to protect it against geohazards. The work presented here demonstrates the need for comprehensive and multidisciplinary geohazard analyses for offshore infrastructure projects.

Keywords: Landslide; rockfall; earthquake; geotechnical and geophysical data integration

1 INTRODUCTION

Submarine cables are an essential component enabling the effective operation and integration of offshore energy systems. They are necessary for transmitting electricity generated by offshore renewables such as solar and wind to onshore grids, supplying power to offshore oil and gas installations, and facilitating the transfer of electricity between two locations separated by water. This paper describes a geohazard study for a submarine cable passing through fjords with challenging soil conditions and highly variable bathymetry. The main geohazards evaluated included submarine slope stability and rockfalls along the cable corridor triggered by earthquakes.

The next section describes the regional one-dimensional (1D) slope stability analyses used to identify critical slopes. Section 3 then outlines the two-dimensional (2D) slope stability analyses, and section 4 presents the rockfall analyses. Finally, section 5 discusses the results of the geohazard study and potential mitigation measures. All analyses are performed for static conditions (unknown triggering mechanism) and for earthquake scenarios corresponding to 100-year and 10000-year return periods. The design earthquake loads are based on a site specific probabilistic seismic hazard analysis.

2 1D REGIONAL SLOPE STABILITY ANALYSIS

We first performed a regional 1D slope stability analysis of the entire project area using a modified version of the screening tool described in Carlton et al. (2017, 2018). The purpose of the 1D slope stability analysis was to identify the most critical locations where landslides could impact the proposed cable route. We first integrated the available geological, geophysical, geotechnical and earthquake data to define the slope angle, soil shear strength, soil thickness, and earthquake loading for a 10 m x 10 m grid of points over the entire project area. The soils were mostly marine hemipelagic clay with some interbedded sand layers. Then, for each grid point, the screening tool performs 1D static and pseudo-static infinite slope stability analyses as well as estimates the seismically induced permanent displacements using the methods of Rathje and Saygili (2009) and Jibson (2007).

The results of the screening tool showed that there were several areas with low estimated factors of safety and high predictions of displacement. Critical locations for more advanced 2D slope stability analyses were then selected based on the results of the 1D analysis as well as the overall elevation change of each slope (i.e. larger slopes with potentially larger failure volumes were prioritised over smaller slopes).

3 2D SLOPE STABILITY ANALYSES

3.1 Methodology

For each of the identified critical slopes, we performed 2D finite element analyses in the program PLAXIS using the SHANSEP NGI-ADP constitutive model for the clay layers, the Mohr-Coulomb model for the sand layers, and the linear elastic model for bedrock. The SHANSEP NGI-ADP model can account for soil shear strength anisotropy, as well as the effect of the overconsolidation ratio and an initial static shear stress (i.e. sloping ground) on the shear strength.

Each 2D analysis is based on both site specific and regional data, with many critical locations having CPT and boreholes located on the slopes. The soil layering is based on the borehole and sub-bottom profiler data, and the unit weight from laboratory measurements. The shear strength was based on CPT measurements correlated to triaxial tests. Anisotropy ratios were derived from a limited number of tests as well as experience from similar soils in nearby projects and were the same for all slopes. For depths below the available CPT and borehole data, the bottom layer was extrapolated to the depth indicated as the top of bedrock or hard glacial till by the geophysical data.

Figure 1 shows some of the selected critical slopes. Each image shows the sub-bottom profiler data along with the start (green dot) and end (red dot) points of the slope modelled in PLAXIS. The locations of available CPT and borehole data near each slope are also shown. Figure 2 shows the PLAXIS model as well as the slope angle and soil thickness for one slope. The maximum slope angles and soil thicknesses on all the selected slopes ranged from 15-25° and 10-50 m.

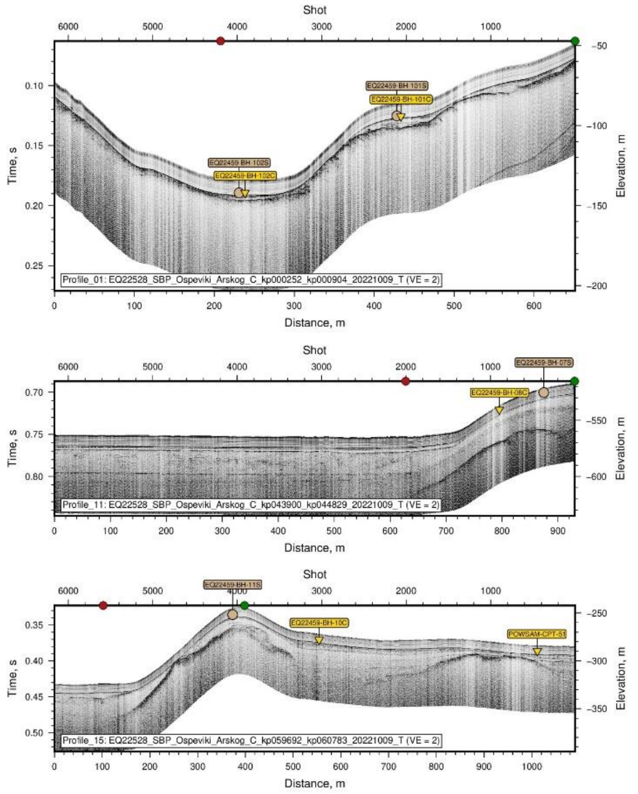

Figure 1. Sub-bottom profiling images of critical slopes 1-3 (top to bottom) showing the start (green dot) and end (red dot) of the modelled slope, as well as the locations of boreholes (tan circles) and CPT (orange triangles)

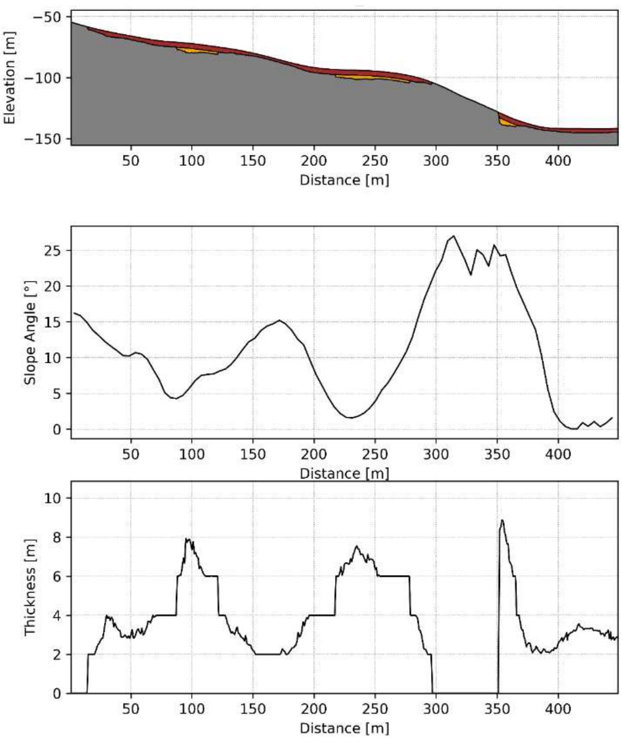

Figure 2 PLAXIS model (top), slope angle (middle) and soil thickness (bottom) for slope 1. Grey is bedrock or hard till, red and orange represent different soil layers.

3.2 Results

Figure 3 shows the most likely failure planes for the slopes shown in Figure 1 for static and pseudo-static conditions. In general, as the earthquake shaking intensity increases, the estimated failure volume increases. For slopes with simpler geometries such as slope 2, there is one distinct failure plane. For more complicated geometries such as slope 1 and 3, there are several potential failure planes.

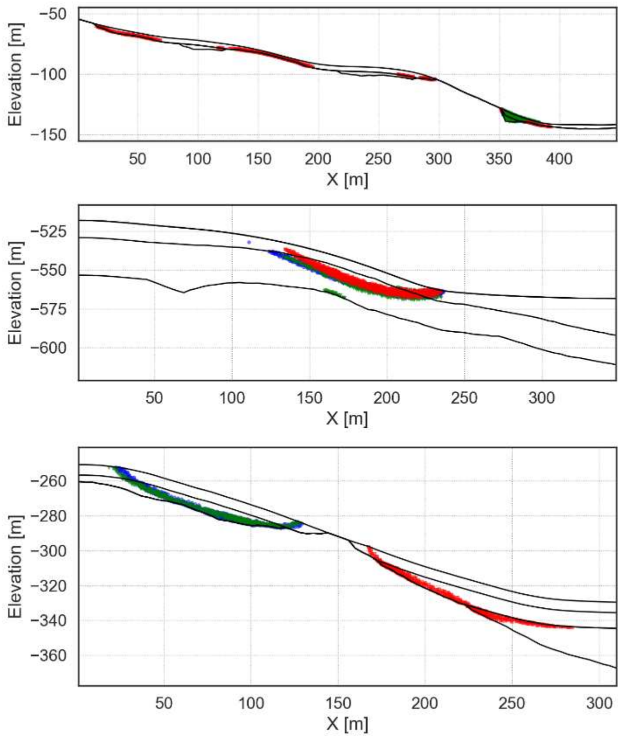

Figure 3 Predicted most likely failure planes for slopes 1-3 (top to bottom) for static conditions (blue), and 100-year (green) and 10000-year (red) return period earthquakes

4 ROCKFALL ANALYSES

4.1 Selection of critical locations

Critical areas for rockfall hazards were selected as locations with outcropping rock and slopes greater than 40° perpendicular to the cable route. Outcropping rock was identified from the bathymetry and sub-bottom profiling data. Figure 4 shows an example of a selected location. 2D profiles were then extracted for the cross-section closest to the cable route at each location and used to estimate rockfall runout distances.

4.2 Methodology

To estimate rockfall runout distances we assumed a single falling rock of variable size and shape. The maximum falling velocity of a rock is the terminal velocity obtained in free fall in water. The terminal velocity is obtained when the friction force is balancing the gravity force and can be estimated as:

$$v^2 = \left((\rho_R - \rho_w) * g * V\right) / (0.5 * C_D * \rho_w * A) \quad (1)$$

where v is the velocity (m/s), ρ_R is rock density (kg/m^3), ρ_w is water density (kg/m^3), g is gravity (m/s^2), V is rock volume (m^3), A is exposed area of rock (m^2) and C_D is drag coefficient. C_D for a sphere is 0.3 and for most irregular rock shapes is higher.

The runout distance S (m) for a falling rock on a flat surface can then be estimated as:

$$S = \frac{\rho_s}{\rho_s - \rho_w} * \frac{v^2}{(2 * C_F * g)} \quad (2)$$

where ρ_s is soil density, C_F is the friction coefficient and v is the rock velocity when hitting the flat surface. The velocity when hitting the flat surface is assumed here to be the terminal velocity (equation 1), which is a conservative assumption because any bouncing or rolling along the fjord flank will reduce the velocity. The friction coefficient takes into account the apparent

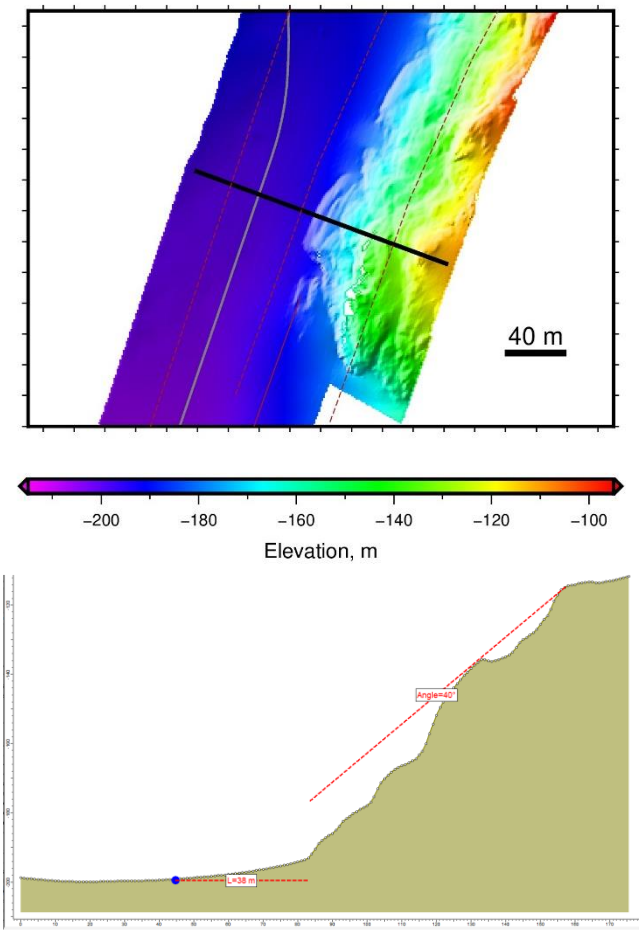

Figure 4 Example rockfall analysis location. Top: the bathymetry with cable route in grey and profile in black. Bottom: profile cross-section with blue dot marking the cable location and L showing the distance to the slope foot.

Coulomb friction between the moving rock and the seafloor, the effect of spin reduction, dynamic friction due to deformations of the seabed, as well as water drag on the rock. However, it does not take into account the penetration of the rock into the seafloor, which is a conservative assumption because the seafloor consists of soft clay and any falling rocks will most likely penetrate considerably.

4.3 Results

Due to the uncertainties in the size and shape of the potential falling rocks, we estimated runout distances for rocks with diameters of 1-3 m, C_D = 0.3-0.5, and C_F = 0.6-1.0. We chose diameters of 1-3 m because these give volumes that are common in subaerial rockfalls seen in fjords. We then compared the estimated runout distances (S) with the distance of the cable from the foot of the slope (L in Figure 4). The results showed that for two locations the estimated runout distances were larger than the cable distance from the foot of the slope for rock diameters of 1 meter and the most conservative drag and friction coefficients, and for rock diameters of 3 meters and the most favourable drag and friction coefficients.

5 CONCLUSIONS

The 2D slope stability analyses show some profiles have low factors of safety for the static and 100-year return period scenarios. Mitigation measures for these slopes could include alternate routes, rock dumping at the toe of the slope, or trenching at the head of the slope. It will be extremely difficult to mitigate against the very low probability 10000-year return period earthquake scenario at all locations. Therefore, we recommend preparing contingency plans to facilitate inspection and repair as fast as possible to limit down time if such an event does occur.

For the submarine rockfall analyses, two locations were predicted to have a high probability for rockfall runout to reach the power cable. However, there was no clear indication of past rockfalls at these two locations. Some areas of scattered boulders were observed on the high resolution multibeam surveys at the bottom of the fjord in other locations, but it is unclear if these boulders were due to past rockfalls or were transported by glaciers. As a result, the probability of rockfall release was deemed to be very low. Because the probability of a rockfall hitting the cable is the rockfall release probability multiplied with the probability of a rock block reaching the power cable, the probability of a rockfall hitting the cable is also expected to be very low. This implies that specific mitigations measures against rockfalls are not necessary.

This assessment ensures the safe and reliable design and installation of a subsea cable, mitigating potential geotechnical risks and informing necessary mitigation measures to protect it against geohazards. The work presented here demonstrates the need for comprehensive and multidisciplinary geohazard analyses for offshore infrastructure projects.

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AUTHOR CONTRIBUTION STATEMENT

Carlton: Conceptualization, Project administration, Formal analysis, Data Curation, Writing- Original draft. **Fornes, Reutz, Kveldsvik and Vanneste**: Formal analysis, Data Curation, Writing – review & editing. **Albarrán Martin and Brooks**: Supervision, Funding acquisition, Writing – review & editing.

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