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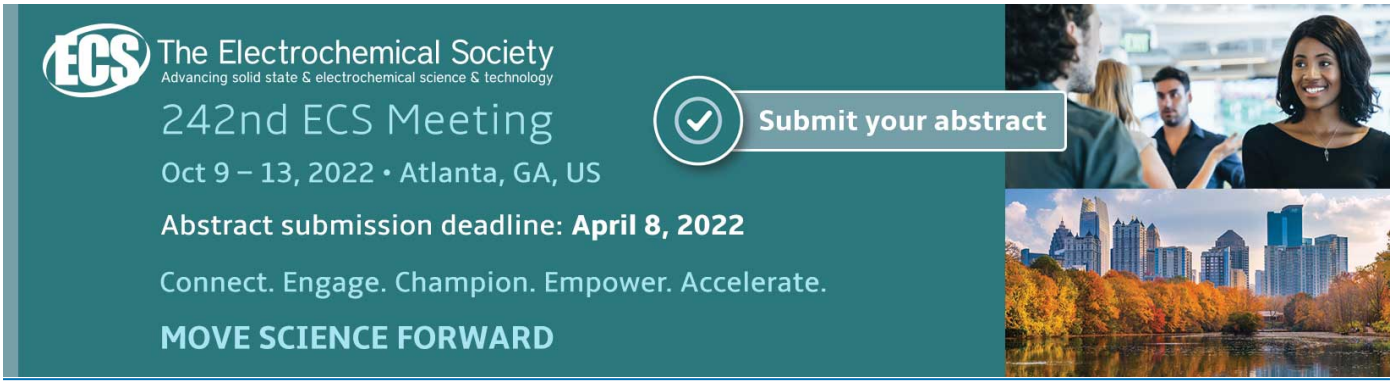

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Stability of the Gunneklev Fjord sediments

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Abstract. The seabed of the Gunneklev Fjord, with exceptionally soft contaminated sediment, is to be capped. The sediment, containing, among others, mercury and dioxins mixed with natural mud, has an undrained shear strength less than 1 kPa and thickness up to 2.5 m. To reduce the potential for leaching of mercury and dioxin from these sediments, Hydro Energy AS developed a remediation plan for Gunneklev Fjord which includes capping of the contaminated sediment with either sand or a mixture of sand and active charcoal. This paper presents an assessment of the risk associated with the cap placement over the contaminated sediment. The potential for the cap causing sliding of the sediment, which could re-expose even more severely contaminated layers and spread the contaminated material, was analysed deterministically and probabilistically. The sediment's undrained shear strength and thickness and the cap thickness were modelled as random variables. The deterministic analyses gave a safety factor over 3. The probabilistic analyses indicated, however, that the probability of sliding can be high for areas where the seabed inclination is steeper than 1:50, and if the average undrained shear strength is less than 0.4 kPa. The analyses highlight the importance of careful cap placement on the sloping seabed of the fjord, and the need to control the cap thickness. The analyses were used to support decision-making on the design of the cap and the placement method.

1. Introduction

Gunneklev Fjord is a landlocked fjord (i.e. a long, narrow, deep sea inlet between cliffs) located 2 km southwest of Porsgrunn, close to the Herøya Industrial Park in Telemark, Norway (figure 1). Sludge from industrial activities started in 1928-1929 has contaminated the bottom sediments in the fjord. The contaminants include mercury (Hg), dioxines ($C_4H_4O_2$) and other pollutants such as TBT and PAH (tributyltin-products and polycyclic aromatic hydrocarbons). The contamination is contained in a sediment layer with maximum thickness of 2.5 m. This sediment is exceptionally soft with shear strength less than 1 kPa. If the sediment layer slides, it poses a significant threat of spreading contaminants over extensive areas of the fjord and may even re-expose more severely contaminated layers.

The Norwegian Environment Agency imposed on Hydro Energy AS to undertake a cleaning up to reduce the potential for leaching of mercury and dioxin from the sediments in Gunneklev Fjord [1]. Hydro Energy AS plans to remediate Gunneklev Fjord to reduce the spreading of contaminated mud. One of Hydro Energy's remediation measures is to cover the contaminated sediment with an isolating cap consisting of either sand or a mixture of sand and active charcoal [2] [3] [4]. The soft sediments appear to have sufficient bearing capacity to support the capping material up to approximately 20 cm. If the capping material becomes thicker than 20 cm, there is a risk for bearing capacity failure and sliding. Thus, it is important to control the thickness during implementation of the cap.

To ensure a safe implementation of the remediation plan, Hydro Energy, together with the Norwegian Environment Agency, decided to evaluate the risk of sliding due to the cap placement on top of the soft sediment. To evaluate the risk, both deterministic and probabilistic analyses of stability and bearing

capacity of the Gunneklev Fjord sediments were calculated for the initial conditions (before capping) and for different cap thicknesses (after capping). This paper presents the results of the analyses of the slope stability. The stability of the contaminated sediment layer was analysed with an infinite slope model.

The paper first describes the Gunneklev Fjord and the top sediments. It then describes the approach for the deterministic and probabilistic analyses and discusses the choice of input parameters. The results are presented together with a discussion of the significance of the results.

2. Gunneklev Fjord and sediment properties

The contaminated area in Gunneklev Fjord is located in a densely populated area in Porsgrunn and extends over about 770 000 m^2 (figure 1a). The water depth varies from 1.5 to 7 m. The soils beneath the contaminated sediment is soft, and in some parts sensitive clay. In this study, the fjord was divided into two areas: the "steep" area with inclination larger than 1:100 and the "gentle" slope area with inclination smaller than 1:100 (figure 1b). In the steepest part of the seabed, many of the zones have an inclination larger than 1:50. The thickness of the sediment varies over the entire fjord. The sediment layer is thickest in the area with steep sea bed in the north and northwest. The maximum measured thickness was 2.5 m. Over many parts of the fjord in the south and in the east, the thickness of the sediment is between 0.1 and 0.5 m.

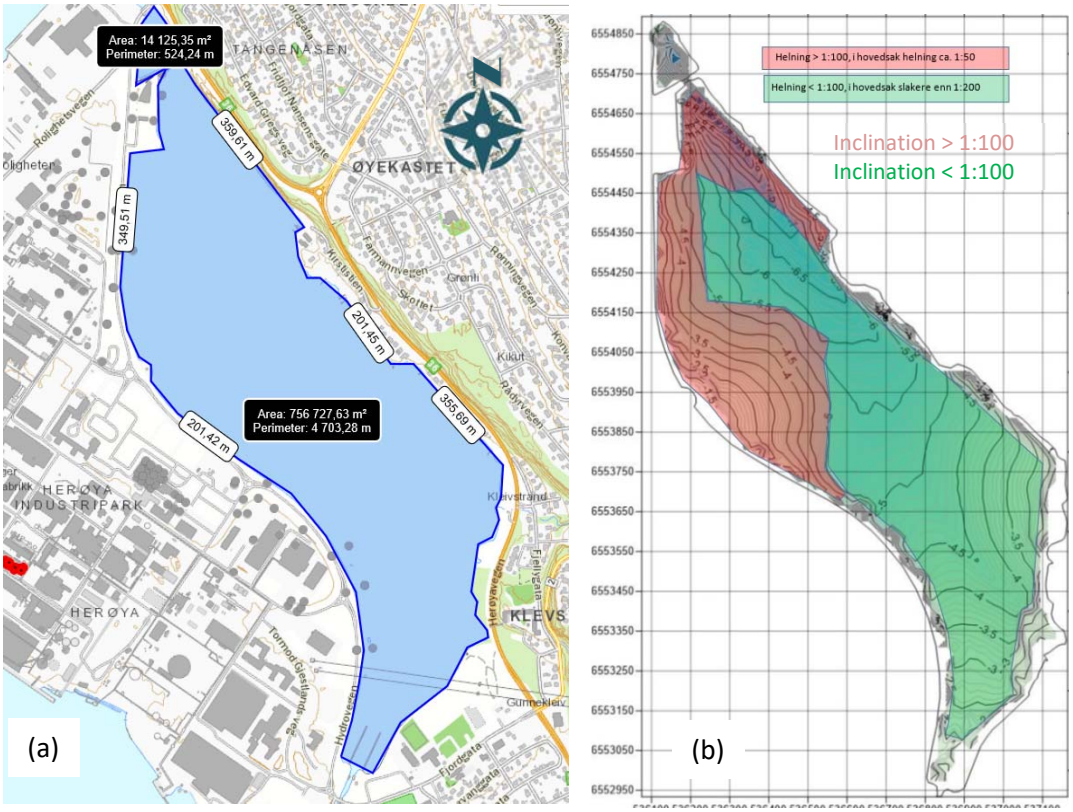

Figure 1. Map of Gunneklev Fjord at Herøya Industry Park, Porsgrunn (a) location and areal extent (b) seabed inclination.

Hydro Energy AS developed a remediation plan for the Gunneklev Fjord which included capping of the contaminated sediments. The contaminated sediment at the bottom of the fjord is however exceptionally soft with water content by weight of 400–900%. It was not possible to take undisturbed samples of the sediment due to the low shear strength. Laboratory tests show that the sediments have a

remoulded shear strength around 0.1 kPa in 8 out of 10 specimens. Other specimens show remoulded shear strength below 0.8 kPa. Given the low undrained shear strength, there is a threat that the cap can initiate sliding in the sediment layer. This would result in re-exposure of even more severely contaminated layers underneath and further spreading of the contaminants. Both deterministic and probabilistic stability analyses were therefore carried out to assess the risk associated with the cap placement.

3. Infinite slope model

The contaminated sediments and the cap in the Gunneklev Fjord can be assimilated to an "infinite slope" with much larger length (*L)* than height (*H*) (figure 2a). Laboratory tests suggest that the sediments at the bottom of the in Gunneklev Fjord are relatively homogeneous both spatially and with depth in the contaminated sediment layer. Figure 2b and 2c gives examples of the quality of the clay/mud sediment. An infinite slope model was selected to estimate the stability of the sediment without and with the cap. Placing the mixed sand-charcoal cap over the sediment will lead to an increase in pore water pressure in the sediment which is unlikely to dissipate quickly due to the low permeability of the clay/mud. The resistance under undrained conditions is therefore critical for stability. The clay layer underneath the contaminated sediment has considerably higher undrained shear strength than the sediment layer. Thus sliding due to the cap placement is likely to occur in the sediment layer and governed by the undrained shear strength of the contaminated sediment. Figure 2a shows the slope model and the soil parameters in each layer used in the analysis.

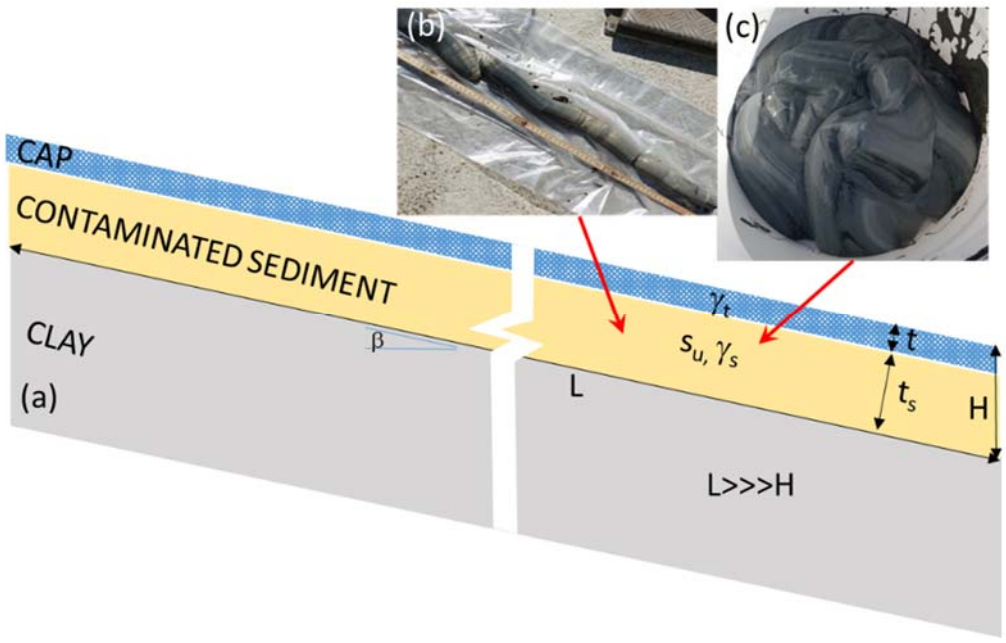

Figure 2. (a) Simplified model of infinite slope used to calculate stability of contaminated sediment in Gunneklev Fjord; (b) a tube sample of the contaminated sediment; (c) a remoulded sample of the contaminated sediment.

The factor of safety (*F*) for the infinite slope was estimated using the following equation:

$$F = \frac{L \times s_u}{G \times sin\beta} = \frac{s_u}{((\gamma_s - 10) \times t_s + (\gamma_t - 10) \times t) \times sin\beta} \quad (1)$$

where

L: Length of the slopes (m)
G: Weight of the sediment per meter length (kN/m)

s_u: Undrained shear strength of the contaminated sediment (kPa)
t_s: Thickness of the contaminated sediment layer (m)
γ_s: Total unit weight of the sediment (kN/m^3), $\gamma'_s = (\gamma_s - 10)$ is the submerged unit weight
t: Thickness of the cap (m)
γ_t: Total unit weight of the capping material (kN/m^3), $\gamma'_t = (\gamma_t - 10)$ is the submerged unit weight
β : Inclination of the slope (rad)

4. Probabilistic approach

Monte Carlo simulations were used for the probabilistic analysis in this study. The same infinite slope model as for the deterministic analysis was used (equation 1). The probabilistic analysis takes into account the uncertainty in the input variables (i.e., undrained shear strength, thickness of the contaminated sediment and thickness of the cap) by assuming that they vary randomly. Each random variable is defined by a set of statistical parameters: mean (μ), standard deviation (σ) and probability density function (PDF) (table 1). The random variables are modelled by generating values randomly and using these random values for the calculations. This means, for each calculation in a Monte Carlo simulation, a set of random input values was generated from the μ, σ and pdf of the random variables. Each Monte Carlo simulation requires a large number of calculations, each with a different combination of input values for the random variables. A calculation is treated as a "failed slope" if the factor of safety is less than 1. The probability of slope failure (P_f) is the ratio of the proportion of failed slopes over the total number of calculations in a Monte Carlo simulation. Over 10 million calculations using equation 1 were performed for each Monte Carlo analysis presented in this paper. The analyses were done with Matlab (MathWorks). In this study, the undrained shear strength of the contaminated sediment was assumed to have infinite horizontal and vertical correlation lengths. Thus, only one random value of shear strength was applied for the entire layer of contaminated sediment in each simulation.

Three parameters were modelled as random variables: undrained shear strength of the contaminated sediment (s_u), thickness of the sediment (t_s) and thickness of the cap (t). These parameters were treated as random because of their high uncertainty and their strong influence on the calculated factor of safety, and thus on the probability of failure P_f. The unit weights of the contaminated sediment (γ_s) and of the capping material (γ_t) also varied to some degree, but their variation was relatively small. To reduce numerical computing time, constant (non-random) values were used for the two total unit weights: γ_s= 13kN/m^3 and γ_t=17 kN/m^3. The sediment total unit weight (γ_s) was calculated from 10 disturbed samples of the sediment taken by cylinder sampler. The total unit weight of the capping materials (γ_t) was based on experience with this type of materials.

Variation in seabed topography causes the slope variation of the sediment layer. Preliminary deterministic calculations showed that the area with gradient less than 1:100 had very high factor of safety. The probabilistic analysis focuses therefore on the areas with slope gradient steeper than 1:100 shown in figure 1b.

5. Analysis parameters

It was not possible to take undisturbed samples of the contaminated sediment due to its extreme low shear strength. Therefore the mean and standard deviation of the undrained shear strength ($\mu(s_u)$ and $\sigma(s_u)$) were chosen based on experience with the undrained shear strength of industrial sludge and very soft clay [5] [6]. In the deterministic analyses, the factor of safety was calculated with all parameters constant and equal to the mean value (table 1). The deterministic analyses were carried out with three value of s_u: 0.4, 0.5 and 0.6 kPa. The probabilistic analyses were conducted with three sets of PDF's for the undrained shear strength, with mean values: $\mu(s_u)$ of 0.4, 0.5 and 0.6 kPa respectively. A standard deviation equal to 0.2 kPa was used in all probabilistic analyses, The coefficient of variation (σ/μ) was thus 50%, 40% and 33% respectively.

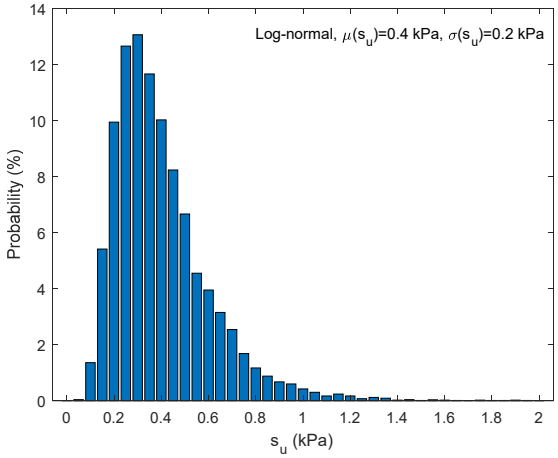

Figure 3. Example of randomly generated s_u values in Monte Carlo simulations ($\mu(s_u)$=0.4 kPa and $\sigma(s_u)$=0.2 kPa).

A lognormal PDF was assumed for the s_u of the contaminated sediment because it has the advantage of excluding negative values (which are unrealistic for s_u). An example of the distribution of generated random s_u is shown in figure 3.

The stability analyses focused on the "steep" area in Gunneklev fjord where the measured thickness of the contaminated sediments lies between 0.5 and 2.5 m. Based on a limited number of measurements of the sediment thickness, the mean value $\mu(t_s)$ was estimated as 1 m, with standard deviation of $\sigma(t_s)$=0.2 m. A lognormal distribution was assumed for the sediment thickness.

The cap is to be placed in a few consecutive layers in a normal implementation process. The thickness of each layer can vary depending on the method of cap placement. In this paper, the mean and standard deviation of the cap layer thickness ($\mu(t)$ and $\sigma(t)$) were estimated based on experiences from similar projects in Norway (Sandefjord Fjord [7], Fiskerstrand Verft in Sula municipality [8] , Trondheim Harbour [9]). In the probabilistic analyses, it was assumed that each layer had an average thickness of 5 cm with a standard deviation of 2 cm. Figure 4 shows the probability density functions of the cap thickness used as input in the analyses, with 1, 2, 3 and 4 layers of 5 cm average capping material. The combined mean thicknesses became 5, 10, 15 and 20 cm, while the standard deviation of the combined thicknesses were 2, 2.8, 3.5 and 4.0 respectively. Log-normal distribution function is assumed for the cap thickness.

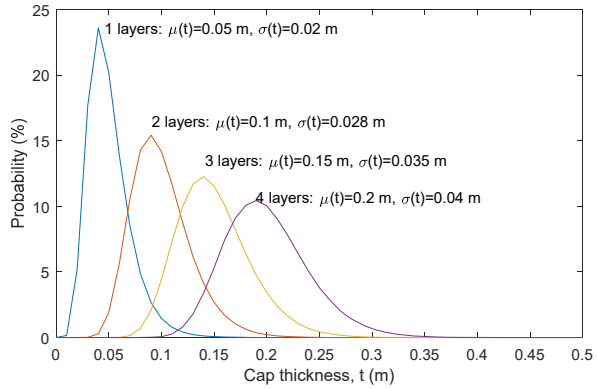

Figure 4. Probability density function of the thickness of the cap, for 1 to 4 layers of 5cm ($\mu(t)$=0.05 m and $\sigma(t)$=0.002 m).

The influence of the slope inclination was dealt with sensitivity analyses. Four slope inclinations were analysed: 1:L = 1:25, 1:50, 1:75 and 1:100. Table 1 summarises the input parameters used in the deterministic and probabilistic analyses.

Table 1 Input parameters for the deterministic and Monte-Carlo analyses of stability

Parameter	Notations	Unit	Mean (μ)	Standard deviation (σ)	PDF
Undrained shear strength	s_u	kPa	0.4-0.6	0.2	Lognormal
Thickness of sediment	t_s	m	1	0.2	Lognormal
Unit weight of sediment	γ_s	kN/m^3	13	0	Constant
Thickness of the cap	t	cm	0 - 20	0 - 4	Lognormal
Unit weight of the cap	γ_t	kN/m^3	17	0	Constant
Slope inclination	$1:L$	--	1:25 - 1:100	0	Sensitivity analysis

The deterministic and probabilistic analyses of stability were performed for both the existing situation before capping, and after placement of the cap.

For the existing situation before capping, the P_f was estimated for four different slope inclinations (1:25, 1:50, 1:75 and 1:100). For situation with the cap, probabilistic analyses were performed with $1:L$ = 1: 50. Four cases were studied to illustrate the influence of the variation in parameters:

Case 1: Random s_u, constant t_s=1 m
Case 2: Random s_u, random t_s
Case 3: Random s_u, constant t_s which gives similar P_f to Case 2.
Case 4: Random s_u, constant t_s from Case 3 and random cap thickness t

6. Results

6.1. Case 1, base case, random s_u

Figure 5 shows that the deterministic F reduces with increasing slope inclination and/or decreasing s_u, as expected. The deterministic F is relatively large, F>3 for all cases analysed. The probabilistic results show, however, that the P_f increases as the slope becomes steeper and/or reducing $\mu(s_u)$. For the lowest mean undrained shear strength ($\mu(s_u)$ = 0.4 kPa), the failure probability becomes quite high ($P_f = 10^{-2}$) for a slope of 1:25, the failure probability reduces to 10^{-4} for a slope of 1:50.

The results show that even though the deterministic F-values are high, the P_f can be quite high when the s_u is modelled as a random variable instead of a constant deterministic value. The results highlight the importance of accounting for the uncertainty in the s_u of the contaminated sediment in the evaluation of slope safety.

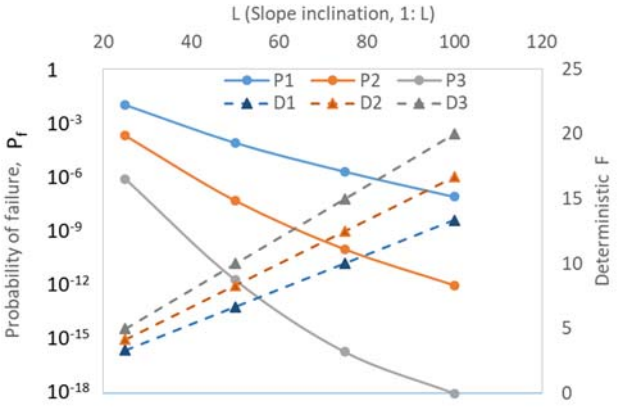

Figure 5. Deterministic factor of safety (F) and failure probability (P_f) vs slope inclination ($1:L$) before cap placement.

D1: Deterministic s_u= 0.4 kPa
D2: Deterministic s_u= 0.5 kPa
D3: Deterministic s_u= 0.6 kPa
P1: Probabilistic $\mu(s_u)$=0.4 kPa
P2: Probabilistic $\mu(s_u)$=0.5 kPa
P3: Probabilistic $\mu(s_u)$=0.6 kPa
Thickness of sediment t_s=1 m

6.2. Case 2, effect of random t_s

In this case, both the s_u and the t_s were modelled as random variables in the probabilistic analyses. Figure 6 shows that the P_f increases when both s_u and t_s are varied randomly (Analyses P4-P6) compared to the base case where only s_u was a random variable (Analyses P1-P3). For example, P_f increases from 1.0×10^{-2} (Analysis P1) to 1.5×10^{-2} (Analysis P4) for the lowest $\mu(s_u)$= 0.4 kPa and the steepest slope (1:L=1:25). These results show that ignoring the variability in sediment layer thickness can lead to unconservative risk assessment in cases where there is considerable uncertainty.

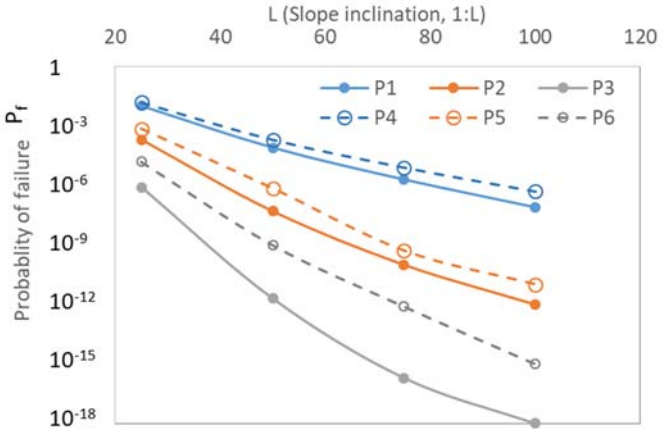

Figure 6. Failure probability (P_f) vs slope inclination (1:L) before cap placement.

Probabilistic analyses with random s_u and constant t_s=1 m
P1: $\mu(s_u)$=0.4 kPa
P2: $\mu(s_u)$=0.5 kPa
P3: $\mu(s_u)$=0.6 kPa

Probabilistic analyses with random s_u and random t_s
P4: $\mu(s_u)$=0.4 kPa, $\mu(t_s)$=1 m
P5: $\mu(s_u)$=0.5 kPa, $\mu(t_s)$=1 m
P6: $\mu(s_u)$=0.6 kPa, $\mu(t_s)$=1 m

6.3. Case 3, same failure probability as Case 2

A trial calculation was done to find a constant t_s value that would give a similar P_f as for Case 2. The purpose was to find a constant t_s value to reduce calculation time for the probabilistic analyses, while still taking into account the uncertainty of t_s. Figure 7 shows that a constant sediment thickness of 1.1 m leads to P_f that are relatively close to the P_f from Case 2, particularly for the most critical cases with 1:L<1:50 and $\mu(s_u)$=0.4 kPa. The analysis with different thickness of capping materials in Case 4 were therefore conducted with a constant value of t_s = 1.1 m.

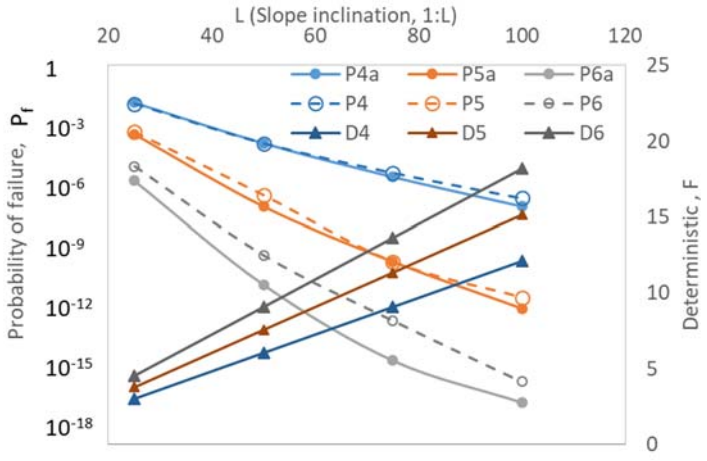

Figure 7. Failure probability of failure (P_f) vs slope inclination (1:L) before cap placement.

Probabilistic analyses with random s_u and constant thickness t_s = 1.1 m
P4a: $\mu(s_u)$=0.4 kPa
P5a: $\mu(s_u)$=0.5 kPa
P6a: $\mu(s_u)$=0.6 kPa

Probabilistic analyses with random s_u and random t_s
P4: $\mu(s_u)$=0.4 kPa, $\mu(t_s)$=1 m
P5: $\mu(s_u)$=0.5 kPa, $\mu(t_s)$=1 m
P6: $\mu(s_u)$=0.6 kPa, $\mu(t_s)$=1 m

Deterministic analysis with t_s= 1.1 m
D4: s_u=0.4 kPa
D5: s_u=0.5 kPa
D6: s_u=0.6 kPa

6.4. Case 4, Probability of failure with the cap, with random s_u, constant t_s from Case 3 and random t.
Deterministic and probabilistic analyses were performed for the placement of the capping material in four successive layers. Each layer had a mean thickness of 5 cm and a standard deviation of 2 cm. Table 2 lists the input parameters for the slope stability under placement of the cap.

Figure 8 presents the results of the deterministic and probabilistic analyses. The deterministic F decreases with increasing cap thickness, but the F remains higher than 4 even for the lowest s_u = 0.4 kPa combined with the thickest cap t=20 cm (Analysis D7). The failure probability P_f, on the other hand, increases with cap thickness, and P_f becomes larger than 10^{-3} when the cap thickness reaches 10 cm for $\mu(s_u)$=0.4 kPa. These results highlight the importance of controlling the thickness of the cap.

Table 2 Input parameters for stability analysis with the cap

Parameter	Unit	Mean, μ	Standard deviation, σ	PDF
Undrained shear strength, s_u	kPa	0.4; 0.5; 0.6	0.2	Lognormal
Thickness of sediment, t_s	m	1.1	0	Constant
Thickness of the cap, t	cm	0; 5; 10; 15; 20	0; 2; 2.8; 3.5; 4	Lognormal
Slope inclination, $1:L$		1:50	0	Constant

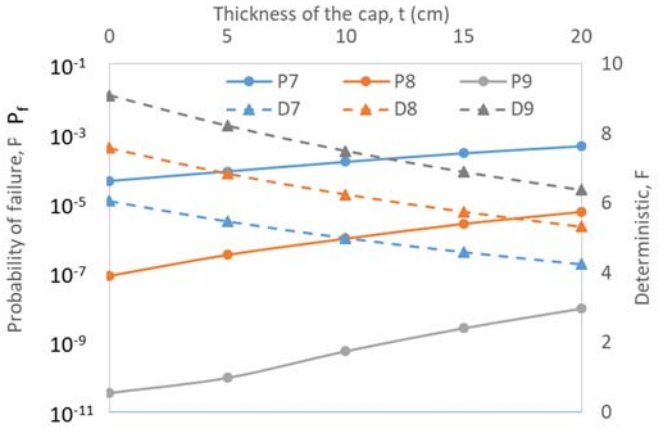

Figure 8. Failure probability (P_f) vs cap thickness (t) for slope inclination ($1:L$) = 1:50.
Probabilistic analyses with random s_u and constant thickness t_s = 1.1 m
P7: $\mu(s_u)$=0.4 kPa
P8: $\mu(s_u)$=0.5 kPa
P9: $\mu(s_u)$=0.6 kPa
Deterministic analysis with t_s= 1.1 m
D7: s_u=0.4 kPa
D8: s_u=0.5 kPa
D9: s_u=0.6 kPa

7. Decision-making on mitigation measures

There are serious consequences with the leaching and spreading of contamination should a slope failure occur in Gunneklev Fjord under the placement of the rehabilitating cap. It is suggested that the threshold for an upper acceptable probability of failure be set at 10^{-3} for slope stability (i.e. a probability of failure less than 1 in 1000). At this probability of failure, the thickness of the cap must be less than 10 cm if the mean undrained shear strength is 0.4 kPa or less.

The results of the deterministic and probabilistic analyses indicate that the Gunneklev underwater slopes with inclination less than 1:50 and mean shear strength $\mu(s_u)$>0.4 kPa have an acceptable nominal failure probability (P_f<10^{-3} before capping). The placement of a 10-cm cap would increase the nominal probability of sliding above 10^{-3}. The placement of a 20-cm cap would result in a high probability of sliding in the areas where the slope inclination is steeper than 1:50, which could result in extensive sliding and contaminant spreading.

In view of the results of the probabilistic analyses and the potential consequences, Hydro Energy AS decided in agreement with the Norwegian Environment Agency, to carry out pilot tests with capping in three test areas in the Gunneklev Fjord, in order to both check the available resistance to sliding and to develop an effective and sustainable method for placing the capping materials, and thus reduce the uncertainty with respect to the thickness of the cap.

The test capping was designed with both 20-cm thickness cap and one 5-cm thickness cap in the "gentle" area where the probability of slope failure is very small. For the field test in the area with gentle slope, the allowable accuracy in the cap thickness was set to +10/-5 cm [10]. Due to the variability in the properties of the contaminated sediment, larger deviations from these allowable tolerances could lead to capping material punching-through the contaminated sediment, and causing further spreading the contaminant. In the steep slope areas, it was decided to test the mitigation measure with placing a 5 cm thick layer with a tolerance of ± 2.5 cm [10]. The small tolerance value is to minimize the potential of the capping material causing slope instability leading to further spreading of contaminant in the fjord.

8. Summary and conclusions

The comparison between probability of failure for different cases and the deterministic factor of safety shows the importance of including the uncertainty in the analysis of slope stability. It is especially important in the case where the input parameters have high uncertainty as demonstrated for the case of the very soft clay mud at the bottom of the Gunneklev Fjord. The probabilistic analyses show that the failure probability can be quite high when the uncertainty in key parameters is taken into account, even though the deterministic factor of safety is very high. Thus, there is real danger of deterministic analyses underestimating the potential for failure. The results also show that the combination of the uncertainties on several parameters can increase significantly the probability of failure of a slope. For the Gunneklev Fjord remediation, the placement of the capping materials needs to be designed in such a way to reduce the uncertainty and failure probability to an acceptable level. The study also demonstrates that probabilistic analyses can be used effectively to assist decision making in cases where the parameters are highly uncertain.

9. Acknowlegdment

The authors wish to acknowledge Hydro Energy AS for the permission to publish the results of the analyses for Gunneklev Fjord.

10. References

[1] Miljødirektoratet 2015 *Pålegg om tiltaksplan* Dato: 7/5-2015
[2] NIVA 2015 *Beslutningsgrunnlag og tiltaksplan for forurensede sedimenter i Gunneklevfjord* Rapport nr. 6796-2015 Delrapport fra akt. 4. den, NIVA 5/2-2015
[3] NIVA 2015 *Beslutningsgrunnlag og tiltaksplan for forurensede sedimenter i Gunneklevfjorden* Rapport nr. 6922-2015 NIVA datert 11/11-2015
[4] Multiconsult 2017 *Vurdering av metode for oppryddingstiltak mot forurenset sjøbunn* Rapport nr. 616978-RIGm-RAP-001-rev02 Dato 6/2-2017
[5] O'Kelly B 2006 Geotechnical properties of municipal sewage sludge *Geotechnical and Geological Engineering* **vol. 24** p. 833–850
[6] O'Kelly B 2013 Undrained shear strength-water content relationship for sewage sludge *ICE Proceedings Geotechnical Engineering* 166(6):576-588
[7] Asplan Viak AS, DNV GL, NGI, 2016 *Tiltak forurenset sjøbunn Sandefjord-Prosjekteringsrapport tildekking*. 606405-01-DP Rev. 1. Dato17.11.2016
[8] NGI 2012 *Evaluering av gjennomføring av testtildekking på TBT-forurenset sediment utenfor Fiskerstrand verft i Sula kommune* Dok. nr. 20171139-00-123-R. Dato. 13.01.2012
[9] NGI 2013 *Pilottest tynntildekking Fagervika - Feltrapport 2013*. Dok.nr. 20120405-03-R. Dato. 21.07.2013
[10] NGI 2019 *Gunneklevfjorden - Tildekking. Tiltaksbeskrivelse, kontrollplan - Overvåkningsplan for testtildekking* Dok. nr. 20170636-03-R Dato: 09-09-2019