Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-661

Slope stability in low plasticity quick clay – Fv. 770 road project in Norway

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ABSTRACT: This work examines the challenges in slope stability evaluations for the Fv. 770 Kolvereid-Nakling road development project, which crosses large, low plasticity marine quick clay deposits along mountainsides, in coastal Mid-Norway. Initial slope stability evaluation employed current Norwegian methodologies, including undrained total stress analysis and drained effective stress analysis, where the most unfavourable results are used as basis for the road design. In several areas along this road, the undrained total stress analysis resulted in the material factor of safety ($\gamma_{m,UDR}$) being near to 1.0 or less, indicating potential instability. The drained effective analysis, however, resulted in a much higher $\gamma_{m,\,DR}$. Recent research suggests that the conventional practice of relying strictly on undrained total stress analysis may be overly conservative for natural slopes. In this study, the recommendations from the SAUNA project were applied. These involve a greater focus on effective stress analysis and a critical review of the input parameters, particularly the friction angle and pore pressure assumptions. By implementing these recommendations and re-evaluating the friction angle based on over consolidation ratio and creep effects, it was possible to significantly reduce the number of slopes classified as critical. The findings highlight the importance of combining clear regulatory requirements with professional judgement and site-specific assessments to avoid unnecessary interventions while ensuring robust slope safety. The study underscores the potential for a more risk-based and nuanced approach to natural slope stability in low plasticity quick clay, provided that thorough investigation and reliable analyses form the basis for decision making.

KEYWORDS: Quick clay, slope stability, road project.

1 INTRODUCTION

County Road Fv. 770 Kolvereid-Nakling, located in the mid-western part of Norway, serves as a vital transportation route for transporting salmon from the town of Rørvik in Trøndelag County. The Fv. 770 project aims to modernise this road, which passes through a coastal area alongside a mountainside exposed to extreme weather conditions due to its proximity to the Arctic Circle, see Figure 1. The road is planned in areas below the upper marine limit in sediments of marine clays, which makes the entire road stretch prone to quick clay and the risk of triggering landslides.

The evaluation of slope stability was carried out based on the methodology in current Norwegian practice, including undrained total stress analysis and drained effective stress analysis. The most unfavourable results were used as a basis for road design. In several sections of this road, the undrained total stress analysis resulted in the material factor of safety ($\gamma_{m,UDR}$) was near to 1.0 or less. The drained effective analysis, however, yielded in a much higher $\gamma_{m,DR.}$ In practice, this means that extensive measures are needed to stabilise the slopes along the Fv. 770 road before the road can be built. The realism of the current practice of evaluating natural slopes as "unsafe" using undrained total stress analysis is being investigated in an ongoing research project at NTNU (Norwegian University of Science and Technology) called SAUNA (SAfety of Urbanized NAtural slopes). Some preliminary conclusions and recommendations (Grimstad *et al.*, 2023; Grimstad and Degago, 2024; Watn *et al.*, 2024) are used in this paper to reevaluate the results from the Fv. 770 road project and discuss the advantages and challenges of implementing the recommendations in geotechnical practice in Norway.

2 LOW PLASTICITY NORWEGIAN MARINE QUICK CLAY

Marine clay was deposited in salt water during the last deglaciation of Scandinavia around 10 000 years ago. The following uplift of the land were followed by freshwater leaching, which led to a reduction of salt content from about 35 g/l to 0-5 g/l. This process has resulted in weaker bonds between the clay particles, that were originally deposited in salt water. However, the open structure of the clay particles remains unchanged and stable until subjected to loads beyond its strength. When the open structure collapses, it transforms into liquid slurry with an undrained shear strength of ≤1.27 kPa.

The plasticity of a clay is usually described with a plasticity index, I_P, which is the difference between the liquid limit, w_L, and the plasticity limit, w_P, also known as Atterberg limits. The Norwegian Geotechnical Society defines a clay as a low-plasticity clay when $I_P < 10\%$ (NGF, 2011). Low plasticity in brittle materials, such as quick clay, results from a combination of the sediment composition, high silt content, and the leaching process, all of which reduce the Atterberg limits, plasticity index, and activity (Mitchell and Soga, 2005).

3 EVALUATION OF NATURAL SLOPES IN NORWAY

The guideline for construction in areas with quick clay deposits and other material with brittle failure properties by the Norwegian Water Resources and Energy Directorate (NVE, 2019) requires that slope stability calculations are performed both for short-term (undrained total stress analysis, $\gamma_{m,UDR}$) and long-term stability (drained effective stress analysis, $\gamma_{m,DR}$). The

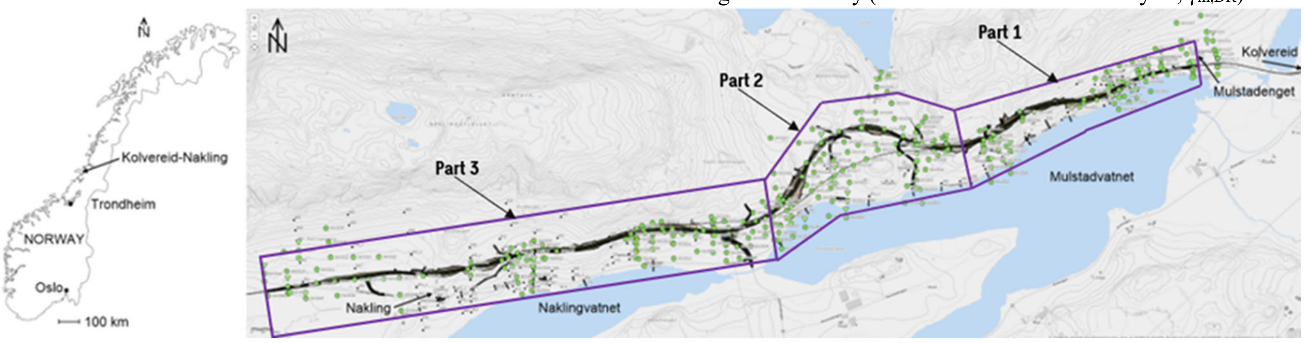

Figure 1. Location of the Fv. 770 Kolvereid-Nakling.

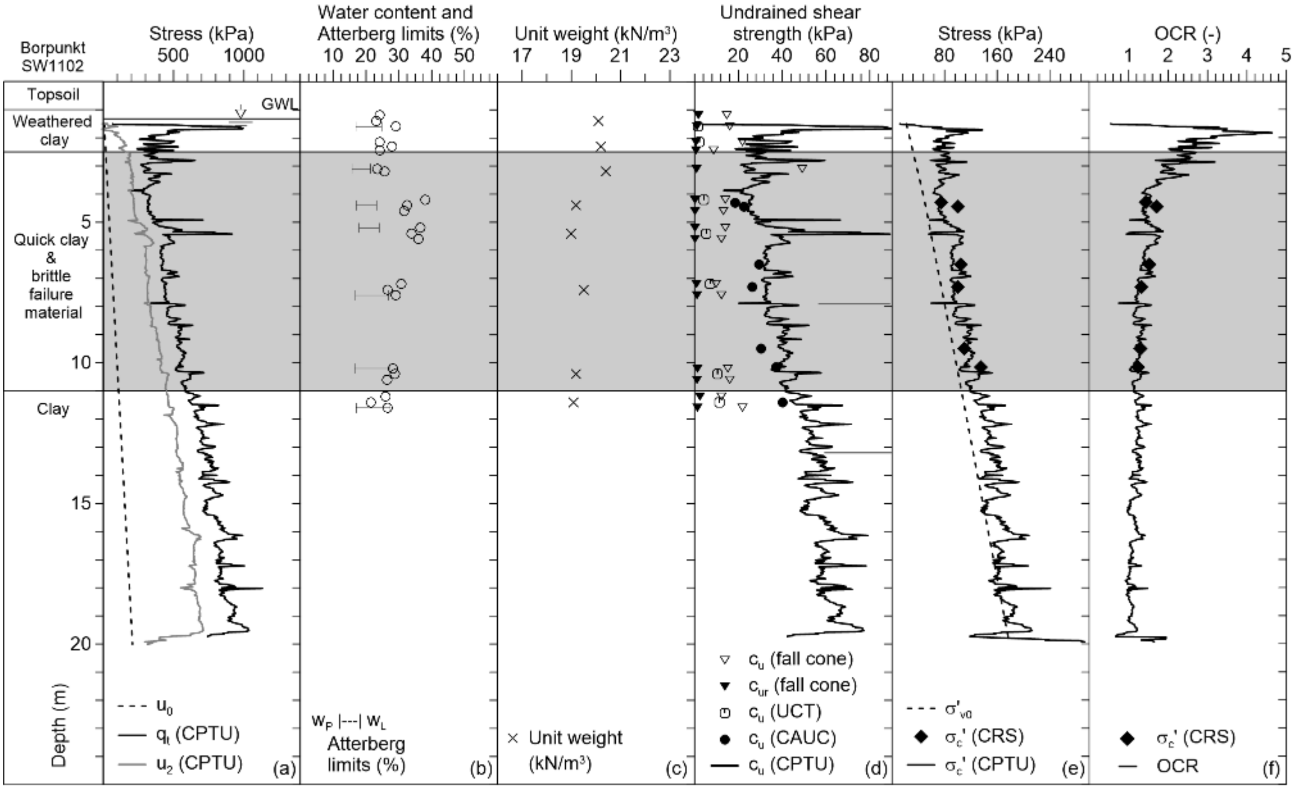

Figure 2. Geotechnical profile of the Mulstadenget clay.

requirements apply for mapped hazard zones where regulations for construction work and urban developments are strict.

- For slopes in the hazard zone for quick clay landslides that are outside the influence area of the measure, the safety requirement $\gamma_{m,DR} \geq 1.25$ and the robustness requirement $\gamma_{m,UDR} \geq 1.20$ apply.
- NVE, NPRA, and Bane NOR have additional requirements for both $\gamma_{m,UDR}$ and $\gamma_{m,DR}$ that are triggered in connection with construction measures:
  - If the measure worsens stability, an absolute safety factor of $\gamma_{m,UDR} \geq 1.6$ and $\gamma_{m,DR} \geq 1.25$ are required.
  - For measures that do not worsen stability, the safety requirement is $\gamma_{m,UDR} \geq 1.40$ and $\gamma_{m,DR} \geq 1.25$.
  - With lower safety, $\gamma_{m,UDR}$ and $\gamma_{m,DR}$ must be increased proportionally according to the procedures described in NVE (2019). Applicable only for change in terrain or by using light weight aggregates.

The safety factor requirements ($\gamma_{m,UDR}$ and $\gamma_{m,DR}$) are independent from each other.

4 GROUND CONDITIONS AND MATERIAL PROPERTIES

Several parts of the current road are planned to be built alongside a steep slope with the lake Mulstadvatnet and Naklingvatnet below, as illustrated in Figure 1. The ground investigations were carried out along the planned road stretch between 2023 and 2024. A total of 258 total soundings and 51 CPTU soundings were conducted. Additionally, 46 piezometers were installed, and 102 piston samples (54 mm) and 69 piston samples (75 mm) were extracted. The piezometers were placed in several depths at the top and bottom of the slope, also in the middle of the slope in some places, as in accordance with recommendations by NVE (2019). The pore pressure was monitored for approximately one year to get an overview of seasonal variations connected to runoff and precipitation.

The ground conditions can be described as challenging due to large deposits of marine quick clay along the mountain slopes. The thickness varies from a few meters near the mountainsides to 35-40 meter near the lakes. The clay is close to normally consolidated, with an OCR close to 1.0 and an undrained shear strength generally between 20-40 kPa. Generally, the clay contains a lot of silt, sand and gravel. In the areas where the rock surface is steep, the amount of coarse material caused significant difficulties in extracting undisturbed soil samples. Figure 2, Figure 3, and Figure 4 displays geotechnical profiles from part 1, 2 and 3 of the project, respectively.

The undisturbed samples were transported shortly after sampling and tested within one week after sampling to avoid an additional disturbance due to storage (Amundsen and Thakur, 2019). The quality of the samples was of good to fair quality based on the $\Delta e/e_0$ criteria (Lunne, Berre and Strandvik, 1997), especially for the 75 mm undisturbed piston samples. However, the amount of sand and gravel resulted in many samples of poor quality. This especially affected the samples taken from Ryphammaren, Figure 4, where the sample had a considerably higher silt and gravel content. This resulted in very few successfully extracted samples from this part of the project. As a result, we supplemented more CPTUs in this location and used CPTU interpretation for evaluation of material parameters, instead of oedometer and triaxial tests.

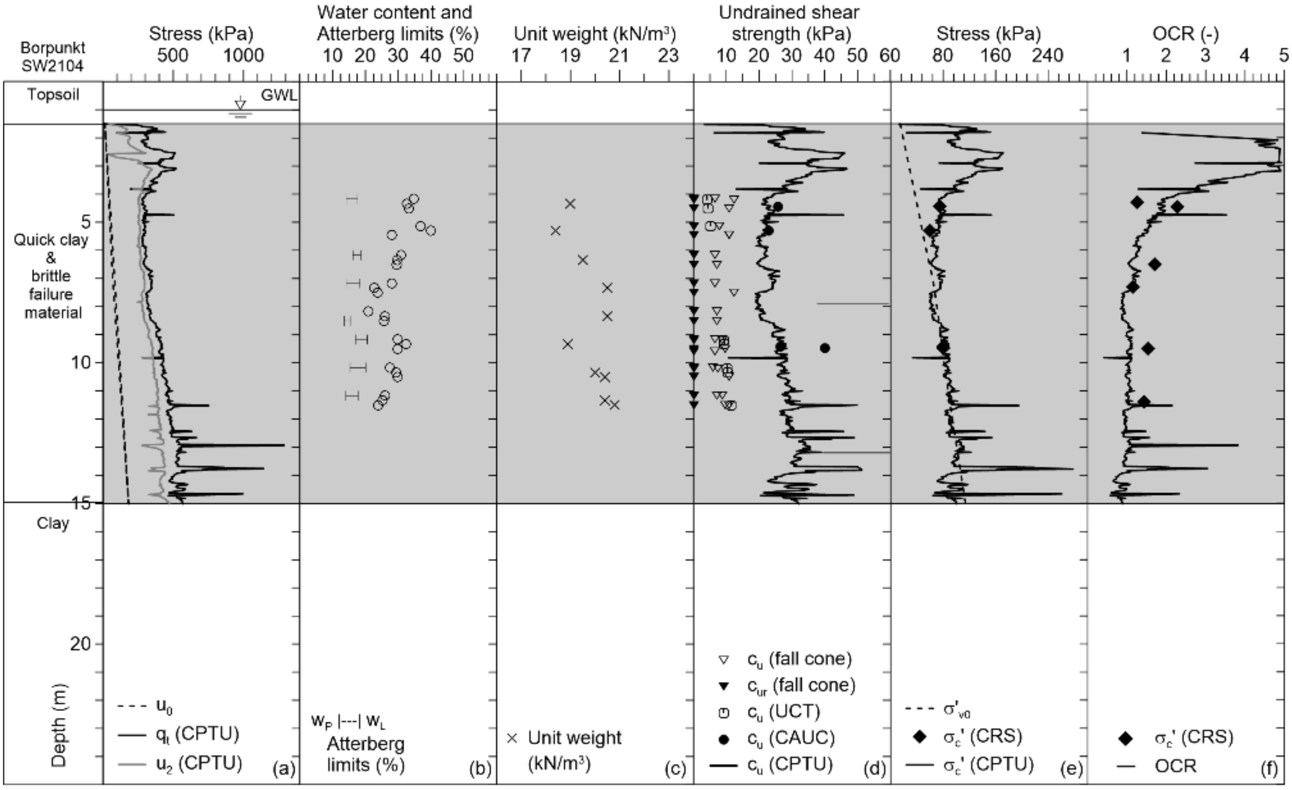

Figure 3. Geotechnical profile of the Leirbogen clay.

Table 1. Material parameters and ADP-ratio used in the stability calculations.

Soil	Unit weight (kN/m³)	Friction angle (°)	Cohesion (kPa)	ADP ratio
Weathered clay/ Dry crust	19	30	0	-
Quick clay	20	27	6.6	1/0.63/0.35
NC-clay	20	27	10.2	1/0.63/0.35
Moraine	19	36	5	-

5 EVALUATION OF SAFETY FACTORS FOR NATURAL SLOPES WITH QUICK CLAY

An extensive amount of ground investigation data was used for evaluation of slope stability along the mountain sides. The factors of safety for the natural slopes were calculated with undrained and effective stress analyses, as required by the guidelines and regulations (NVE, 2019). The calculations were conducted following the established practice in Norway, where the ADP ratio is assumed to be low and friction angle are interpreted directly from an undrained triaxial test, see Table 1. The undrained shear strength profiles are interpreted based on the CAUC test of varying sample quality. The pore pressure profiles used for calculations are based on in-situ measurements from several depths and locations along the slope. The calculations were conducted in GeoSuite Stability 24.0.12.0 with calculation mode BEAST 2003. GeoSuite is the most used program (LEM based) for calculating stability in Norwegian practice. This paper presents the results from stability calculations of natural slopes prior to construction of the road.

The factors of safety are summarized in Tables 2-5, grouped by hazard zones. Most of the calculations resulted in low $\gamma_{m,UDR}$, which implies need for stabilization if the planned road is going to be affected by a potential slide, $\gamma_{m,UDR} > 1.2$. If the road is going to be in the slope, or if the construction of the road affects the stability of the slope in any way, the requirements are even stricter ($\gamma_{m,UDR} > 1.6$).

6 DISCUSSION

6.1 *SAUNA (SAfety of Urbanized NAtural slopes)*

There is still uncertainty regarding current methods for slope stability analysis, especially concerning their ability to distinguish between natural and man-made slopes. An ongoing research project at NTNU called SAUNA is evaluating the current practice and recommendations for slope stability analysis.

Some preliminary conclusions and results from the project are following (Watn *et al.*, 2024):

- It should not be possible to have $\gamma_{m,DR} > 1$ and $\gamma_{m,UDR} = 1$ for natural slopes. There should be a connection between those safety factors. Natural slopes can be analysed only with effective stress analysis if $\gamma_{m,DR} \geq 1.6$. Undrained analysis for robustness requirements should be conducted if $1.25 < \gamma_{m,DR} < 1.6$.
- If $\gamma_{m,UDR} < 1.2$ and $\gamma_{m,DR} \geq 1.6$ the analysis should be reevaluated and new analysis should be conducted.

The underlying assumptions for the recommendations (Grimstad and Degago, 2024) are shortly summarized as follows:

- Conservative input to the undrained stability analysis, such as ADP (Active Direct Passive)-ratios and undrain shear strength profiles. The latter is usually based on disturbed samples and CPTU interpretations that were developed for flat terrain.
- ADP ratios are intended for flat terrain and cannot indiscriminately be used for a natural slope.

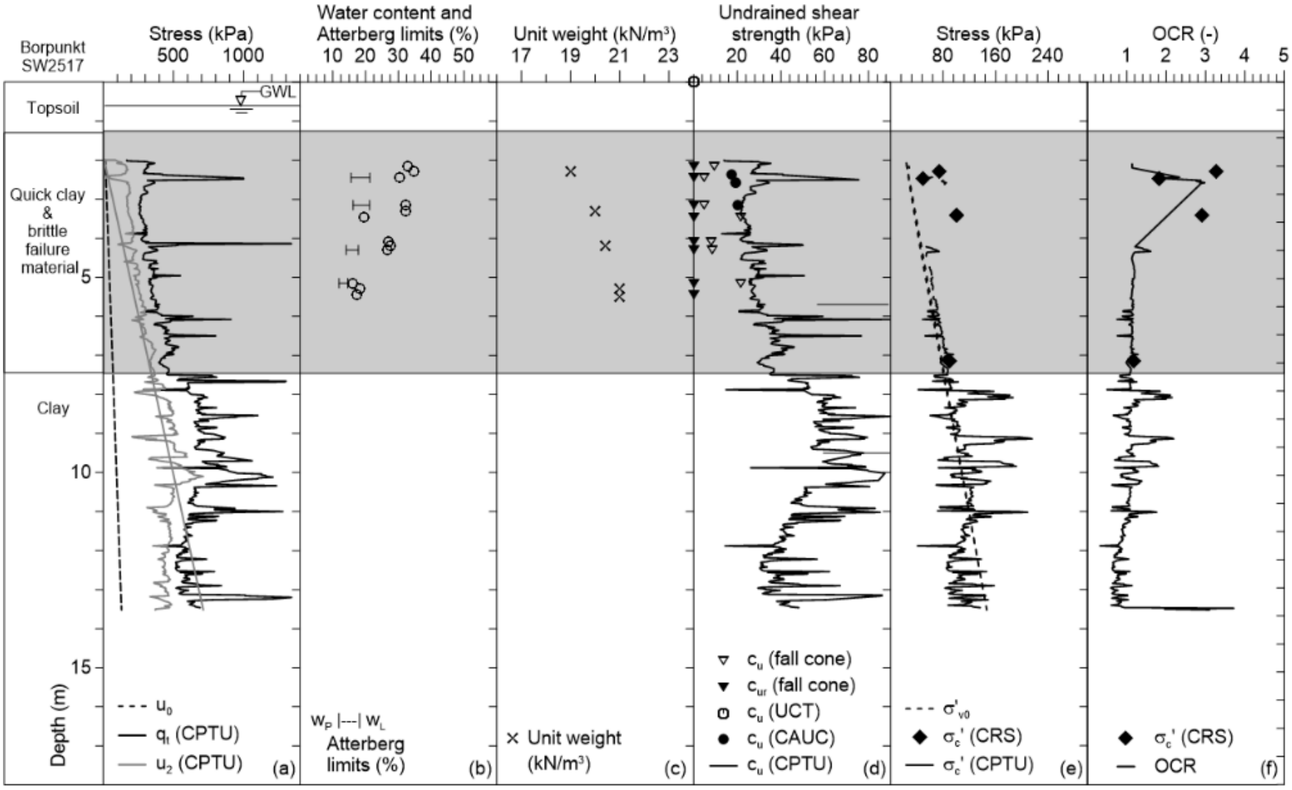

Figure 4. Geotechnical profile of the Ryphammaren clay

- Undervaluation of drained analysis such as ignoring the creep effects and using friction angle from the triaxial test directly, and geological history.
- Assumption of hydrostatic pore pressure distribution in a slope.

7 REEVALUATION OF SLOPE STABILITY - RECOMMENDATIONS FROM SAUNA PROJECT

According to the SAUNA recommendations, the undrained stability analyses for natural slopes are not necessary when $\gamma_{m,DR} > 1.6$. If this recommendation is used directly, without any changes in how the slope stability is calculated, the following observations can be summarized for the Fv. 770 road project:

- Only one of six undrained analyses would have been conducted in the hazard zones Mulstadenget and Mulstadaunet, see Table 2.
- In the next hazard zones, Mulstad, Eldvika and Leirbogen, none of the undrained slope analyses would have been necessary, see Table 3. That means that three slopes where $\gamma_{m,UDR} < 1.2$ would not have been evaluated.
- Only one of six analyses would have been carried out in the hazard zones Ryphammaren and Heimstad where the $\gamma_{m,UDR}$ values are about 1.0, see Table 4.
- In the Nakling and Naklingmarka hazard zones only one of four analyses would have been necessary.

According to the recommendations presented in the SAUNA study (Grimstad and Degago, 2024), it is expected that the factors of safety from undrained and drained analyses should be approximately equal under realistic input parameters, i.e., $\gamma_{m,DR} / \gamma_{m,UDR} \approx 1.0$. In practice, however, a significant discrepancy is observed. Our results show that the ratio between undrained and drained safety factors ranges from 1.27 up to 2.74 across the investigated profiles. This indicates that the current calculation methodologies may systematically underestimate the stability of natural slopes when relying on undrained analyses alone and perhaps overestimate the drained analyses. The evaluation of the slope stability with less strict requirements, that SAUNA project proposes, would significantly reduce the number of undrained analyses, which would result in the same conclusion but would save a lot of time and resources. However, several slopes with low $\gamma_{m,UDR}$ would not have been discovered. That is a concern for practicing geotechnical engineers, as these slopes are currently treated as the most critical by the government requirements (NVE, 2019). Given the consequences of a failure, and the destructive nature of quick clay slides, any future revisions of national guidelines, in accordance with results from the SAUNA project, needs to have a strong academic foundation.

A revaluation of undrained slope analyses would have been interesting to explore, especially by conducting more laboratory tests to see if the ADP ratios are higher than assumed. High-quality samples would also verify whether the undrained shear strength used in the analyses is too conservative. However, this is not practically possible for most of the ground conditions in the Fv. 770 project, as the quick clay is well-mixed with sand and gravel. In that case, even a block sampler (Lefebvre and Poulin, 1979; Emdal *et al.*, 2016) cannot extract undisturbed samples of good quality.

As indicated by the SAUNA project (Grimstad and Degago, 2024) conservative ADP-factors seem to be one of the causes for the underestimation of the stability of natural slopes, with respect to the total stress analysis. For the Fv.770 project ADP-factors have exclusively been chosen in accordance with Norwegian practice based on recommendations given by NVE (NVE, NPRA and Bane NOR, 2014). Site-specific factors have not been determined using passive and direct triaxial tests and conservatively chosen factors may be a contributing factor in this case as well.

A re-evaluation of effective material parameters and conducting a water flow analysis could reduce the $\gamma_{m,DR}$ to a value lower than 1.6 for some of the slopes. Following the proposed dependency between the friction angle and OCR (Grimstad and Degago, 2024), the friction angle should be between 22° and 26° in the Fv. 770 project. That would have reduced the $\gamma_{m,DR}$ significantly and possibly would have led to the same conclusions as the undrained analyses.

There are inherent weaknesses associated with using GeoSuite as a calculation tool, since it doesn't allow for conducting water flow analysis. Water flow is limited to manual input of pore pressure in specific points along the cross section and requires understanding and insight of the designing engineer. The usage of numerical modelling, or other software more versatile with respect to water flow could increase the accuracy of the drained analyses.

Table 2. Slope stability results – Mulstadenget and Mulstadaunet, Part 1 in Figure 1.

Profile	$\gamma_{m,UDR}$	Requirement	$\gamma_{m,DR}$	Requirement
2900	1.16-1.22	≥ 1.20	2.63	≥ 1.25
3050	1.10-1.55	≥ 1.20	2.38	≥ 1.25
3150	1.33-1.57	≥ 1.20	2.51	≥ 1.25
3300	1.01-1.17	≥ 1.60	1.75	≥ 1.25
3400	1.02-1.34	≥ 1.60	1.50	≥ 1.25
3450	1.03-1.12	≥ 1.60	1.81	≥ 1.25

Table 3. Slope stability results – Mulstad, Eldvika and Leirbogen, Part 2 in Figure 1.

Profile	$\gamma_{m,UDR}$	Requirement	$\gamma_{m,DR}$	Requirement
4280	1.15-1.22	≥ 1.20	2.41	≥ 1.25
4400	1.87-2.03	≥ 1.20	3.68	≥ 1.25
4650	1.25-1.29	≥ 1.20	2.85	≥ 1.25
5020	1.10	≥ 1.20	2.26	≥ 1.25

Table 4. Slope stability results – Ryphammaren and Heimstad, Part 2 in Figure 1.

Profile	$\gamma_{m,UDR}$	Requirement	$\gamma_{m,DR}$	Requirement
5200	0.98-1.14	≥ 1.40	1.63	≥ 1.25
5250	1.13-1.70	≥ 1.40	1.89	≥ 1.25
5335	1.04	≥ 1.20	2.85	≥ 1.25
5550	1.07-1.28	≥ 1.20	2.18	≥ 1.25
5910	0.98-1.00	≥ 1.20	1.32	≥ 1.25
5950	1.23	≥ 1.20	1.85	≥ 1.25

Table 5. Slope stability results – Nakling and Naklingmarka, Part 3 in Figure 1.

Profile	$\gamma_{m,UDR}$	Requirement	$\gamma_{m,DR}$	Requirement
6390	1.28	≥ 1.20	1.80	≥ 1.25
6500	1.13	≥ 1.20	1.43	≥ 1.25
7460	1.52	≥ 1.20	2.46	≥ 1.25
7650	1.21	≥ 1.20	1.75	≥ 1.25

Table 6 summarizes results from additional stability calculations, performed on certain profiles at Nakling and Naklingmarka, where we have investigated the effect of choosing friction angle based on the recommendations from the SAUNA project (Grimstad and Degago, 2024). In these additional calculations standardized values for friction angle, based on OCR are used. Calculations have been performed for friction angle of 22° and 26° (if needed). Alteration of friction angle has only been subjected to soil-layers of brittle material or quick clay, and the remaining layers are unaltered. These additional calculations resulted in five profiles that were previously excluded from undrained analyses due to the SAUNA criterions, are now included again due to a $\gamma_{m,DR}$ lower than 1.6.

According to the SAUNA study(Grimstad and Degago, 2024), it is expected that the factor of safety from undrained and drained analyses should be approximately equal under realistic input parameters, i.e., $\gamma_{m,DR} / \gamma_{m,UDR} \approx 1.0$. In practice, however, a significant discrepancy is observed. Our results show that the ratio between undrained and drained safety factors ranges from 1.27 up to 2.74 across the investigated profiles. When recalculating the safety factors, this ratio is reduced considerably to a range between 1.04 and 1.84. This suggests that more realistic input parameters, particularly for the critical state friction angle, contribute to narrowing the gap between undrained and drained assessments and provide a more consistent basis for evaluating slope stability. Nevertheless, the remaining deviation underlines the importance of continued refinement of analytical methods.

Table 6. Slope stability results – Nakling and Naklingmarka, Part 3 in Figure 1.

Profile	$\gamma_{m,UDR}$	$\gamma_{m,UDR}$ *φ=22°*	$\gamma_{m,UDR}$ *φ=26°*	Trigger revaluation
2900	2.63	2.13	-	No
3050	2.38	1.94	-	No
3150	2.51	2.01	-	No
3300	1.75	1.35	1.58	Yes
3400	1.5	-	-	No
3450	1.81	1.77	-	No
4280	2.41	2.01	-	No
5200	1.63	1.25	1.57	Yes
5250	1.89	1.39	1.68	Yes
5950	1.85	1.28	1.57	Yes

The premise for recalculating new safety factors for drained stability is that the actual friction angle is lower than originally assumed. This assumption is based on evaluations presented in the SAUNA article (Grimstad and Degago, 2024). It results in a relatively dramatic reassessment of the findings from CAUA. Figure 5 displays the CAUAs that has been conducted on the Mulstad clay, i.e., Part 1 of the project (Figure 1). In the original calculations, we used a friction angle of 27° with an attraction of 15 kPa. According to Grimstad and Degago (2024) a conservative, yet still fully legitimate, choice of friction angle for further calculations would be 22°, providing no alteration of cohesion. Both friction angles are displayed in Figure 5. The lower friction angle is mainly based on the knowledge that drained mobilization estimated from an undrained triaxial compression test, is known to overestimate the degree of mobilization for a drained fracture (Torpe, 2014; Grimstad and Degago, 2024). Hence, the material will mobilize at lower stresses than indicated by the interpretation of the CAUC, due to the process of tertiary creep in the material. The practical difficulties associated with accounting for tertiary creep in the interpretation of laboratory tests are quite evident, particularly as there is no consensus on how to reduce the interpreted mobilization to the critical mobilization for materials prone to tertiary creep. This is also evident from our study, as presented in Figure 5.

In addition to the inherent uncertainty associated with tertiary creep, it is worth noting sample disturbance as an additional source of uncertainty. Sample disturbance will in most cases lead to the overestimation of the friction angle. As mentioned, sample disturbance is an important factor for the given project, since the amount of sand and gravel resulted in many samples of poor quality. Long and disturbing transport to the laboratory may also have had an impact, even though measures were taken to avoid vibrations. There was a considerable effort made to reduce the sample disturbance, by restricting the storage duration to a minimum.

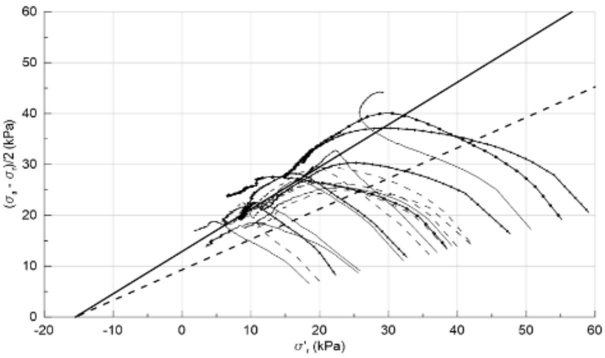

Figure 5. Combined plot of all CAUCs taken from part 1 of the project. Solid line at friction angle of 27°, dashed line at 22°.

8 CONCLUSIONS

The results from this project clearly demonstrate that changes to regulatory assessment frameworks for quick clay slope stability have substantial economic and environmental consequences. When applying recommendations from the SAUNA project, the number of critical slopes requiring stabilization could be reduced by more than 50%. Following the SAUNA recommendations 14 critical slopes would be reduced to only 3 critical slopes initially in this project, when only considering $\gamma_{m,DR} \geq 1.6$. When including revised friction angle criteria, the critical slopes increased to 7. This would have eliminated the need for four counter fills and two lime-cement stabilization areas, resulting in significant savings of both costs and environmental resources(Magar *et al.*, 2026).

However, this streamlining must be balanced against the risk of overlooking slopes that could be vulnerable to undrained failure, particularly when only drained criteria are used as a filter. The societal consequences of a quick clay failure are grave, so regulations must not rely solely on generalized threshold values. Future guidelines must therefore combine clear, objective requirements with strong professional judgement and rigorous site-specific assessment.

For a risk-based and nuanced approach to proceed, it is crucial to ensure the reliability of drained stability analyses, and a thorough understanding of local conditions. Further research and practical experience are needed to confirm that risk-based prioritization consistently provides sufficient safety without unnecessary cost or intervention.

This approach requires that each geotechnical engineer exercises sound professional judgement, for example, when evaluating the potential for rapid loading, groundwater changes, or human-induced interventions in their assessments, and that natural slopes with a higher potential for stress changes leading to undrained conditions are properly identified. There will always be a risk that potentially critical slopes under undrained conditions (i.e., lacking sufficient robustness) are overlooked due to satisfactory drained safety factor, whether this is the result of calculation errors or inadequate evaluations. The premise of these recommendations must be higher confidence in drained analyses than undrained, or that undrained stress state is considered to be unrealistic for the given slope. Whether this is realistic must be verified sufficiently. Thus, a nuanced and case-specific understanding of slope stability is essential to ensure that neither safety nor cost-effectiveness is compromised.

The optimal solution is likely a combined approach i.e. vulnerable slopes should always be thoroughly assessed for robustness, while areas with clearly adequate drained safety can be deprioritized. By carefully calibrating requirements to reflect the true stability of each slope, substantial cost reduction is possible so long as safety is never compromised.

9 ACKNOWLEDGEMENTS

The authors are grateful to Trøndelag County authorities (Trøndelag fylkeskommune) for allowing us to publish the results from the Fv. 770 road project. The authors wish to acknowledge the support from Sweco Norway, especially team manager of geotechnics group in Trondheim, Guri Venvik for encouraging the publication of the results and project lead Mari Sagbakken for her support throughout the project duration

Engineers Oddbjørn Rønning, Morten A. Pettersen, Stig Bjarne Larsen, Didrik Ring and André Bakken are gratefully acknowledged for their skills and knowledge that made challenging ground investigations possible. The authors are also grateful for the good collaboration with the geotechnical laboratory at Multiconsult and ground investigations team at Rambøll for carrying out ground investigations on the lakes.

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