# STABILITY OF NATURAL SLOPES - ROBUSTNESS AND SAFETY


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### KEYWORDS

Slope stability, Quick clay, Natural slopes



### ABSTRACT

Methodology for assessing the stability of natural (existing) slopes in current Norwegian practice is mainly based on undrained total stress analysis (robustness requirement) and drained effective stress analysis (material factor requirement). The two methods are not expected to provide the same material factor (FOS or $\gamma_m$). However, when a slope is standing in drained state, but is really at the same time calculated to be at undrained failure ($\gamma_m$ = 1.0), the material factor should ideally then be uniquely defined at 1.0. Meaning that there should be no calculated margin left to failure in drained state as well. In practice total stress analyses usually give FOS of 1.0 or even less, while the drained effective stress analyses give a significantly higher factor of safety. Based on current regulations and guidelines, the most unfavorable result must then be taken as a basis for design. This frequently mean that extensive measures must be taken to improve the stability, without necessarily being the optimal use of resources. As of today, the rules do not suggest evaluating analysis results from the two analysis methods considering each other. We believe that one must be able to get a uniform picture of the robustness of a natural slope with both methods. Therefore, there is a need to look more closely at the underlying premises and conditions for the slope stability analyses. This work looks at the historical development in the practice of stability analyses. We find some interesting changes in what has been emphasized over time. There is a varying use of undrained total stress analyses with and without the use of anisotropic models, undrained effective stress analyzes, and drained effective stress analyses.



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## 1. INTRODUCTION

Slope stability analysis in geotechnical engineering provides a basis for checking that the required level of safety in the associated regulations is met or to design measures necessary to satisfy the given requirements. Accordingly, the calculated factor of safety (FOS) is of great importance for reliability, economy, and feasibility of a project.

Natural (existing) slopes involving quick clay, by definition, are in a consolidated state, standing under drained conditions with no excess pore water pressure. However, if a failure is triggered by an initial slide, it could lead to a fast and extensive retrogression process making the failure occur under undrained condition. This has led the regulations, from NVE (2020), requiring both the drained and undrained slope stability evaluations, where the undrained slope stability evaluations should be conducted using the total stress approach. The required material factor for the drained analysis is $\gamma_{m,DR} > 1.25$ and for undrained analysis $\gamma_{m,TOT} > 1.20$. With satisfaction of these criteria, the slope is considered safe under existing conditions, i.e. without the need for extra safety measures.

In the recent years we have observed that when conducting area stability evaluations, the consultants responsible for the analyses typically face a contradictory situation of $\gamma_{m,DR} > 1.60$ and $\gamma_{m,TOT} \approx 1.0$.. On one hand, the natural slope is evaluated as safe, yet on the other hand, the natural slope is failing under existing conditions. For a failing natural slope or close to failure, the drained or undrained conditions has no relevance, since natural slopes does not carry excess pore water pressure under their existing condition.

Grimstad et al. (2023) demonstrated this issue using undrained effective stress analyses. They found that a slope with undrained material factor $\gamma_{m,UNDR} \approx 1.20$ could have a drained factor, $\gamma_{m,DR}$, as high as 1.60 (but likely it will be lower), meaning that $\gamma_{m,DR} > 1.60$ should ensure $\gamma_{m,UNDR} > 1.20$. Since this result counters the current Norwegian state-of-practice leading to far-reaching implications, more studies are required before decisive conclusions. Furthermore, we need a clear understanding of why generally the calculated $\gamma_{m,TOT}$ indicates a critical condition while $\gamma_{m,DR}$ indicates a (very) safe situation for natural slopes.

Based on our understanding of how the analyses are done in the current practice and their underlying assumptions, our hypotheses for the discrepancies are briefed as follows:

1) The total stress ADP (Active-Direct-Passive) method gives too conservative results for $\gamma_{m,TOT}$ for natural slopes. The reasons could be:
    a. The ADP factors were originally developed and meant to be used for flat terrain and not for the stress situation in slopes. Aamodt et al. (2021) demonstrated that a modified ADP model

for sloping terrain increases the material factor by 0.10 to 0.20 depending on slope angle.

b. Inputs for active and passive strengths are determined for triaxial condition but used for plane strain problem (Krabbenhøft et al. 2019).

c. The undrained shear strength profiles selected as design profiles are inherently conservative, typically due to sample disturbance.

d. The interpretation of CPTU does not give the peak undrained shear strength for quick clays.

e. Interpretation of CPTU results in slopes is not directly comparable to those established for flat terrains ($K_0$ consolidation) under the hydrostatic pore pressure condition.

2) Since ADP method usually gives conservative results, the drained analyses are commonly undervalued. This led to a practice where various practitioners oversimplify the drained analyses:

   a. Practitioners interpret the friction angle and attraction, for the drained case, directly from undrained triaxial compression tests. Even though studies show that higher strength mobilization levels, for normally consolidated (NC) quick clay, result in tertiary creep that eventually lead to failure. Pusch et al. (2016) found this mobilization level to be $f_{su} \approx 0.85$ based on $s_u$ (which is not directly transferable to the mobilization based on friction angle). Torpe (2014) found that a drained mobilization ($f = \tan\rho/\tan\varphi$) as low as $f = 0.70$ still results in tertiary shear creep rupture within laboratory time frame in undrained triaxial tests on NC quick clay (*OCR* around 1.4). However, it is very difficult to find the critical mobilization from laboratory tests as any sample disturbance will result in over predicting the initial creep rate.

   b. The interpretation of critical friction angle and attraction (cohesion) should also be evaluated in the light of geological history. For instance, if the OCR is much higher than two and a sample is sheared (i.e. on the “dry side”), as results shown by e.g. Leroueil (2001), the Coulomb line (critical state line) will practically be a limitation due to undrained creep swelling followed by tertiary creep. This is very relevant for ravines, see section 2.

   c. Practitioners usually overlook the critical situation in terms of pore pressure. Often only the ground water level (GWL) is identified, and hydrostatic pore pressure distribution is assumed. A ground water flow analysis is seldom conducted despite being highly relevant for sloping terrain. Critical deviations related to seasonal variation and precipitation are not considered.

d. Despite the “independent” interpretation of shear strength in drained and undrained (total stress) condition, the critical cross sections for drained case are not identified independently from the undrained (total stress) case.

The primary purpose of this article is to present a critical review of the current state-of-the practice looking at historical development of the provided guidelines for assessment of stability of natural slopes in quick clay. Secondly, the work aims to establish the basis for a bigger project aimed at giving input for new guidelines for assessing the safety and robustness of natural slopes in quick clays.

## 2. NATURAL SLOPES IN QUICK CLAY

Lyche[1] (NVE 2015) categorized natural slopes into four groups along with the following geotechnical and geological characteristics (NVE 2015).

1) “Even terrain slopes”

Geologically:

- Formed by deposition in an earlier seabed basin, governed by "underlying" topography (rock).

Geotechnically:

- Normally not preloaded (OCR only due to creep) but weathered with 1-3 m of dry crust. Often homogeneous deposits, but proximity to mountains or watercourses often results in more variable conditions regarding layering and pore pressure.

2) “Ravine slopes”

Geologically:

- Formed by erosion in a clay deposition (for example in an even terrain slope)

Geotechnically:

- Ongoing erosion process, including continual development of small slides and surface slips.

[1] Presentation at workshop at NPRA Trondheim, 2014, by Einar Lyche (NVE)

- Marginal stability against shallow slides (liable surface)
- Often critical in triggering quick clay landslides.

3) “Terrace slopes”

Geologically:

- Erosion from large rivers/watercourses ("mega ravines") in marine deposits.
- Completed deposition steps under the withdrawal of the ice.

Geotechnical: (as for ravines)

4) “Submarine slope” (“Marbakke”)

Geologically:

- Formed similarly to a terrain slope above water.

Geotechnically:

- Exposed to wave erosion and to marine erosion forces, such as shore currents or propeller currents (in ports)
- Mapped often in connection with larger development projects.
- Quick clay occurs also off the shore.
- Warning signals about possible landslides are invisible.

**Total stress ADP analyses**

Roughly before 2000, the use of ADP analyses for natural slopes were quite sparce and mostly used for stability evaluations of cuts and fillings. The reference to use of ADP, with NGI code BEAST v2003, for natural slopes came with the development of the GeoSuite package. The main available reference regarding ADP analyses for natural slopes is the stability seminar held at Hell, Norway in 2003[1]. The handbook of the Norwegian Public Road Administration (SVV 1992) “HB016 – Geoteknikk in vegbygging” page 105 states: “*Totalspenningsanalyse … må bare brukes innenfor sitt gyldighetsområde*” – meaning “*total stress analyses… must only be used within its valid domain*”. This means that it is up to practicing engineers to define that domain. In the authors’ understanding, the common practice for evaluating the stability of natural

[1] Karlsrud, Kjell (2003) “Stabilitetsanalyser av skråninger, skjæringer og fyllinger”. Kurs 20.-22. mai 2003, Rica Hell Hotell

slopes varied with respect to how much emphasize was given to the total stress analyses and how they were performed. These variations were observed between different consultant firms, state agencies and regions.

**Drained effective stress analyses**

Over the last years, it seems that in many cases the effective stress analyses of natural slopes in quick clay has been reduced to a mandatory exercise done as formality. SVV (2018) suggest using a friction angle ($\varphi$) as low as lower than 20° for quick clay. With such a low value for $\varphi$, it would be surprising if the total stress analyses would still give the lowest results for the calculated material factor. However, this low $\varphi$ is not the common practice, yet, based on the authors observations, the friction angel interpreted for high strain levels from undrained triaxial test is used (orange solid line in Figure 1). This is typically in the range of 32° - 36° (combined with zero cohesion). The friction angle used in effective stress analyses should consider possible tertiary shear creep (point 2a.).

**Undrained effective stress analyses**

Undrained effective stress analyses (or ESAU) (Svanø and Nordal 1987) has not became a standard method for stability evaluation. Hence, undrained analyses with use of Janbu *D* parameter have not been seen in practice. These type of analyses with $D < 0$ always give some undrained margin of safety if the slope is standing under drained condition. The selection of friction angle from undrained triaxial testing is still questionable, but less than for the drained state since there is some control on the undrained shear strength through *D*. However, the role of shear creep is still not properly accounted for.

**Expectations**

It is expected that total stress analyses should yield the most critical results for slopes on even terrain. On the other hand, for ravine slopes, total stress analyses should give safer results than long term (effective stress) analyses. Due to the possible creep swelling (point 2e.), the drained analyses would be more reliable for ravine slopes. If the pore pressure is not properly evaluated, then the effective stress analyses are surely directly affected (point 2c.). Also, since the interpretation of CPTU are dependent on the initial pore pressure it might also give unreliable results (point 1e.).

With finite element analyses, pore pressures can be better estimated in seepage calculation and drained/undrained safety analyses are both available in mechanical part. However, it is not possible to make direct comparison between drained and undrained failure for the same mechanism in finite element analyses. But, with the method of slices material factor for the same mechanism can compared across the different analyses.

## 3. METHODOLOGY FOR FRICTION ANGLE DETERMINATION

Figure 1 shows a schematic response of undrained triaxial tests run with three different axial strain rates, $\dot{\varepsilon}_{a1} < \dot{\varepsilon}_{a2} < \dot{\varepsilon}_{a3}$, where $\dot{\varepsilon}_{a1}$ represents the slowest possible rate that can still be practically considered as undrained. The figure also shows schematically the response of three different undrained creep tests with different initial mobilization (initially at the same volume). There will be an initial mobilization for which the minimum strain rate during the undrained creep phase will be equal to $\dot{\varepsilon}_{a1}$. Setting this as a critical mobilization line (envelope), here solid green line, it provides the value of $\varphi$ to be used in drained analyses, as higher average mobilizations along a mechanism that would cause creep failure. The dashed green line gives the mobilized friction angle at "point of no return" (for $\dot{\varepsilon}_{a1}$).

Further, as mentioned earlier, tertiary creep limit (critical mobilization) will depend on OCR. In Figure 2a schematic test result on normally consolidated (NC) quick clay is compared to a schematic result of an over-consolidated (OC) quick clay, with the same initial effective stress. As seen, it is expected that the critical mobilization is a function of OCR which in practice means on the natural slope type. "Even terrain slopes" would have an OCR due to aging alone (around 1.4), while in ravine slopes the OCR will depend on the depth of the ravine and position of the point (depth) in relation to the ravine surface. The OCR will depend on depth (the effective stress) in the ravine slope. Alternatively, it is possible to make consideration for this variation by using a representative cohesion and a single value for $\varphi$. This principle is demonstrated in Figure 3.

Figure 4 gives the expected variation in the critical $\varphi$ as a function of OCR. It is assumed that a NC clay (1 day old) will creep to failure even in $K_0$ condition. With inspiration from SHANSEP (Ladd et al. 1977), the following is used:

$$\sin\varphi = \min\left(\frac{1-K_0^{NC}}{1+K_0^{NC}} \cdot OCR^m, \sin\varphi_{CAU}\right) \tag{1}$$

Where $\varphi_{CAU}$ is the "conventional" friction angle from undrained triaxial compression tests (orange solid line in Figure 1). The figure gives some indications of the expected variation in OCR for the categorized slopes and variation in friction angles as hatched areas.

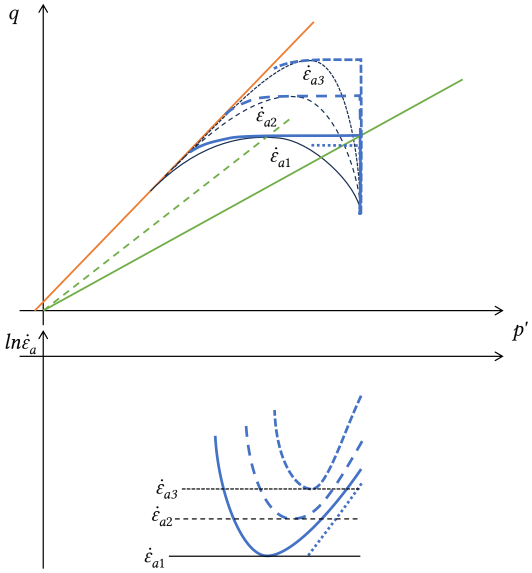


*Figure 1 Schematic behavior of NC quick clay in undrained triaxial tests. Three tests with varying rate $\dot{\varepsilon}_{a1} < \dot{\varepsilon}_{a2} < \dot{\varepsilon}_{a3}$, Four undrained creep tests with varying initial mobilization. Results given in p' – q and p' – ln$\dot{\varepsilon}_a$*

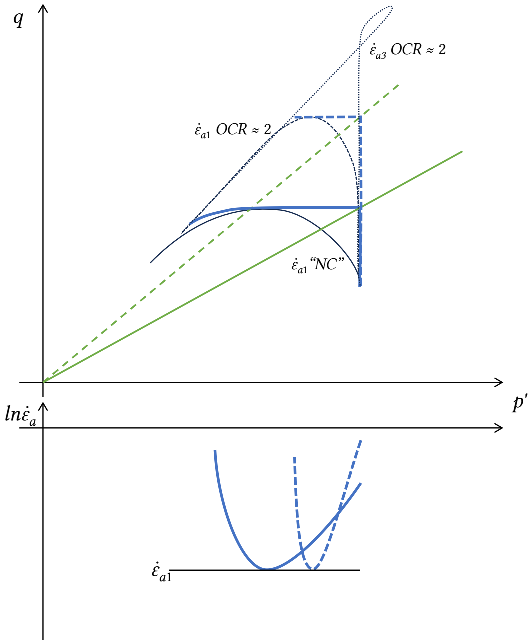


*Figure 2 Schematic behavior of NC and OC quick clay in undrained triaxial tests, both constant rate and undrained creep tests. Results given in p' – q and p' – ln$\dot{\varepsilon}_a$. Critical mobilizations dependent on OCR.*

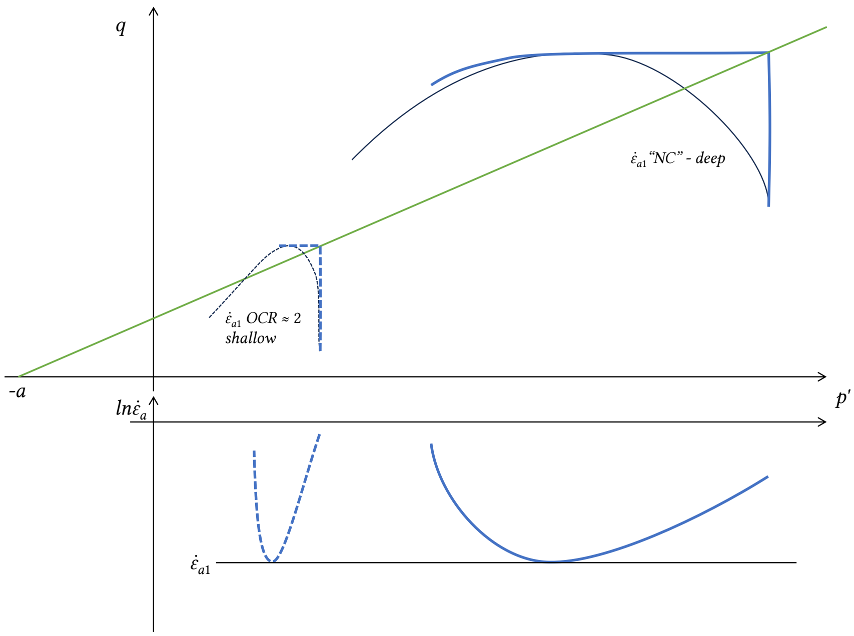


*Figure 3 Schematic behavior of NC and OC quick clay at two different depths (stress level) in undrained triaxial tests, both constant rate and undrained creep tests. Results given in p' – q and p' – ln$\dot{\varepsilon}_a$. Interpreted as constant $\varphi$ and with cohesion/attraction.*

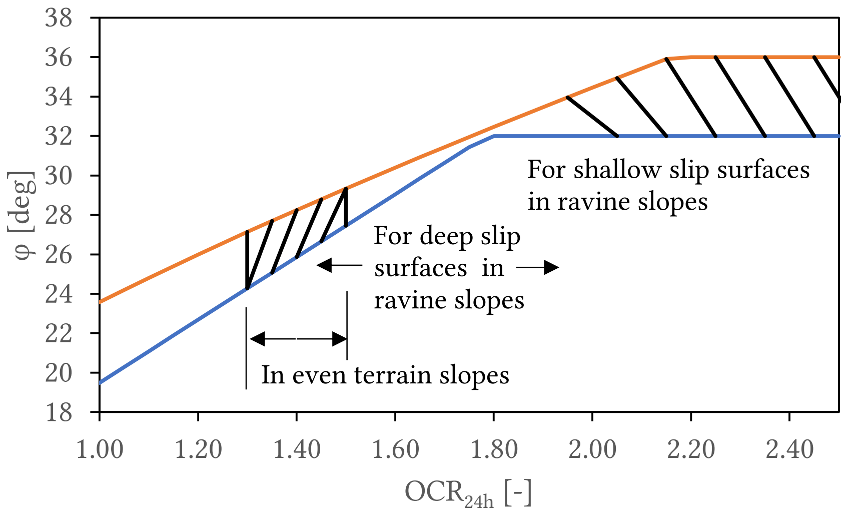


*Figure 4 Friction angle for drained analysis as a function of OCR corresponding to 1 day reference time (with low values for cohesion)*

## 4. EXAMPLE ANALYSIS

In this section, a hypothetical even terrain slope is considered to numerically illustrate the presented methodology. An even terrain slope consisting of dry crust, clay, quick clay, and a permeable layer is considered and analyzed in Plaxis 2D, Figure 5.

Two cases are analysed with varying friction angles. From Figure 4 we see that for an even terrain slope in quick clay a friction angle of 25° is a reasonable value in drained safety analyses, *OCR* ≈ 1.4. While for a sensitive clay, but not quick, 27° could be more appropriate (upper estimate at same *OCR*). The hypothetical case of Grimstad et al. (2023), Figure 5, is re-analyzed with these input parameters (see Table 1). The calculated drained material factor is $\gamma_{m,DR} = 1.47$ and the undrained material factor was found to be $\gamma_{m,UNDR} = 1.23$, using a Janbu $D = 0.0$ and the same values for $\varphi$ (ESAU approach). This result is as expected for the even terrain slope since the undrained analysis gave the lowest calculated safety factor.

For a second case, more unconservative values for the drained analysis, like $\varphi = 29°$ for both quick clay and clay gave $\gamma_{m,DR} = 1.65$. If we assume that drained and undrained analyses give unique simultaneous $\gamma = 1.0$ at failure, linear interpolation implies that $\gamma_{m,DR} > 1.60$ would ensure $\gamma_{m,UNDR} > 1.20$ for cases similar to the (extreme) second case. With a similar line of reasoning $\gamma_{m,DR} > 1.41$ would ensure $\gamma_{m,UNDR} > 1.20$ in the first case.

In case one, the drained failure mechanism (Figure 7) is similar to the undrained failure mechanism (Figure 6). In the second case (Figure 8) the drained failure surface is not in the quick clay and shallower and more local.

Table 1. Parameters

| | Quick clay | Clay | Perm. layer | Dry crust |
|---|---|---|---|---|
| $\gamma$ [kN/m$^3$] | 19.0 | 19.0 | 19.0 | 19.0 |
| $G'$ [kPa] | 2000 | 2000 | 2000 | 2000 |
| $K'$ [kPa] | 4000 | 4000 | 4000 | 4000 |
| $\varphi$ [°] | 25 (29) | 27 (29) | 35 | 30 |
| $k_x = k_y$ [m/day] | 0.001 | 0.001 | 0.1 | 0.1 |
| $K_0$ | 1 - sinφ | 1 - sinφ | 1 - sinφ | 1 - sinφ |

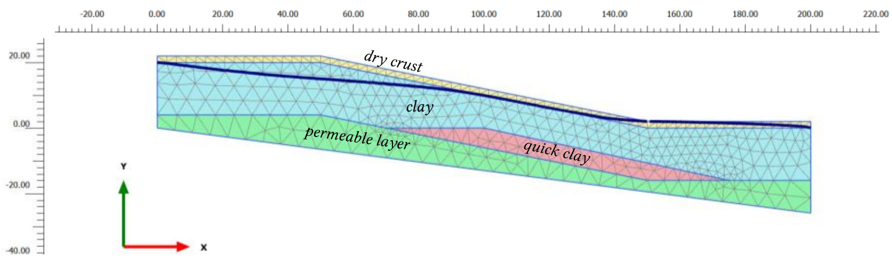


*Figure 5 Geometry of the even terrain slope.*

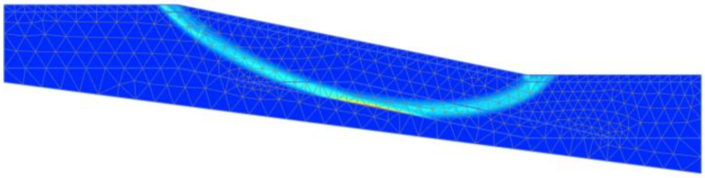

*Figure 6 Undrained failure mechanism (shear strain)*

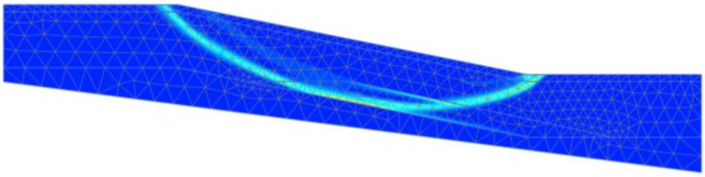

*Figure 7 Drained failure mechanism (shear strain) for case one.*

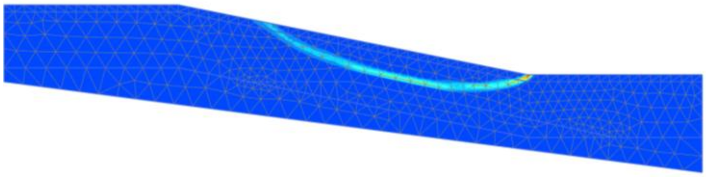

*Figure 8 Drained failure mechanism (shear strain) for case two.*

## 5. CONCLUSIONS

The current practice for stability evaluations often leads to situation where an existing slope in drained state is evaluated as “unsafe” from a total stress based undrained analysis. Possible reasons for such discrepancies are discussed in the article. The main message to take from this review is that ADP analyses have led to too little focus on critical pore pressure evaluation and relevant interpretation of friction angle, to use in drained stability analyses. This also led to a practice where measurement of pore pressure profiles is seldom carried out in projects. The example shown in the article demonstrates that a calculated drained factor of safety higher than 1.6 ($\gamma_{m,DR} > 1.60$), using the proposed interpretation of friction angle, also satisfies the robustness criterion set with undrained factor of safety larger than 1.20 ($\gamma_{m,UNDR} > 1.20$).

Further studies are being carried out in the project to identify an acceptable drained safety level that also ensure sufficient robustness.

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