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Calibration of material factor to account for strain softening in undrained loading of sensitive clays

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ABSTRACT Very sensitive "quick" clays are a challenge in Norwegian road development projects. These clays show significant strain-softening behavior under undrained deformation, which previously partly has been hidden by sample disturbance. However, in recent years sample quality has become better, and the effect of strain softening needs to be accounted for by increasing the material factors in the traditional limited equilibrium methods widely used in practice. The material model NGI-ADPSoft has been used in FE calculations to calculate the effect of including strain softening. Monte Carlo simulation was used to establish a probability distribution for the effect of strain softening, with soil parameters based on an extensive database of laboratory tests on high quality samples. To calibrate the necessary increase of the material factor, equal probability of failure was specified for a material with strain softening behavior as for a perfectly plastic material. The results from this study will be used as a basis for establishing material factors for new guidelines.

1 INTRODUCTION

Very sensitive "quick" clays are a challenge in Norwegian road development projects. These soft clays show significant strain softening behavior under undrained deformations. In previous practice the measured peak undrained shear strengths have been reduced by sample disturbance. However, in recent years sample quality has become better, and the effect of strain softening needs to be accounted for to have the same level of safety in design as before. In the traditional limited equilibrium methods widely used in practice this can be done by increasing the required material factors, such that the probability of failure for a clay with strain softening is the same as for a perfectly plastic material, see Figure 1.

For clays with strain softening response the bearing capacity is stiffness dependent, which limit equilibrium methods are not suited for (Grimstad and Jostad, 2012). FE analyses are therefore necessary to evaluate the effect of strain softening on the bearing capacity. In this study, the construction of a road fill was considered, with the weight of the fill as the active load that may result in failure. For such case, the effect of strain softening can be determined by first increasing the weight of the fill until failure with strain softening included, and then afterwards with perfectly plastic behavior and keeping the same weight constant, incrementally reducing the peak strength values with a factor $F_{softening}$ until failure, see Figure 2.

2 MONTE CARLO FE SIMULATION

FE calculations with the material model NGI-ADPSoft has been used to calculate the effect of including strain softening. To get a realistic distribution of expected values for Norwegian conditions, Monte Carlo simulation was used with soil parameter distributions based on Norwegian sensitive clays.

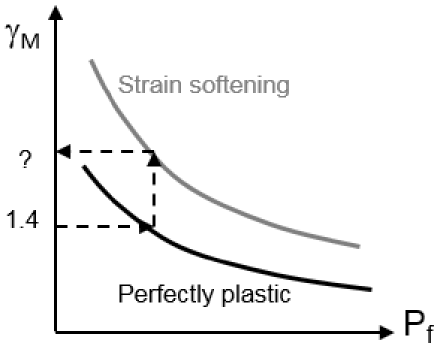

Figure 1. Figure caption. Equal probability of failure Pf in design with material factor γ_M for perfectly plastic and strain softening materials

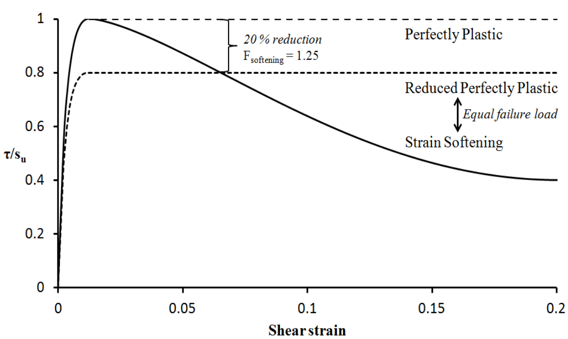

Figure 2. Determination of strain softening correction factor $F_{softening}$

2.1 Material model

The material model used in this study was the model NGI-ADPSoft (Grimstad et al., 2010; Grimstad and Jostad, 2010; Jostad and Grimstad, 2011). Input parameters to the model are anisotropic peak strengths and corresponding failure strains, post-peak strength reductions and corresponding shear strains, and shear band thickness parameters, see Figure 3. To prevent mesh dependency due to shear band localization caused by strain softening a regularization method is implemented in the model, the so-called non-local strain (Brinkgreve, 1994).

In the study, softening behavior was idealized with linear strength reduction, which was found to be valid for the strain mobilized at global maximum load.

2.2 FE model

Plaxis 2D (www.plaxis.nl) was used to model an unlimited slope with construction of a road fill initiating a local bearing capacity failure, which can lead to a forward progressive slide. Figure 4 shows shear strains at maximum fill weight in an FE calculation, including strain softening. This illustrates the softening effect compared to perfectly plastic in Figure 5. For the strain softening case there is not yet a fully developed failure mechanism. While the strength is reduced post-peak in the active zone, the passive strength is not mobilized.

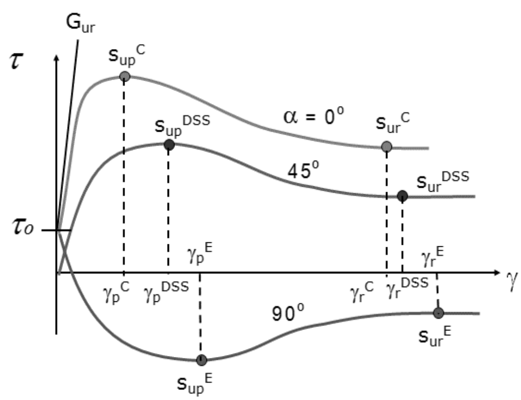

Figure 3. Material model NGI-ADPSoft

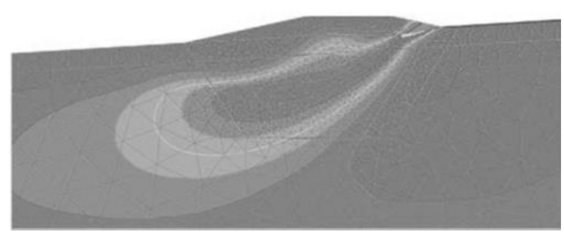

Figure 4. A part of the FE model, total shear strains at max weight with strain softening behaviour

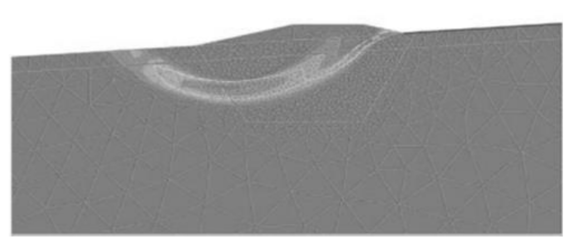

Figure 5. A part of the FE model, total shear strains at max weight with perfectly plastic behaviour

2.3 *Input parameters*

Strengths, stiffnesses and strain softening input parameters were defined by 10 independent variables. The probability distributions of the variables were based on the range of soil properties for normally consolidated sensitive clays in NGIs laboratory database on high quality block (Sherbrooke) samples (Karlsrud and Hernandez-Martinez, 2013). An example triaxial stress-strain curve is shown in Figure 6, where the peak strength is reduced by 20 % at 5 % total shear strain. The undrained shear strength increases linearly with depth, and the top two meters of soil was modelled with perfectly plastic behavior to represent dry crust and a transition zone toward the soft clay. The slope angle, dry crust thickness, K_o and unit weight which were related to the geometry were varied in different cases.

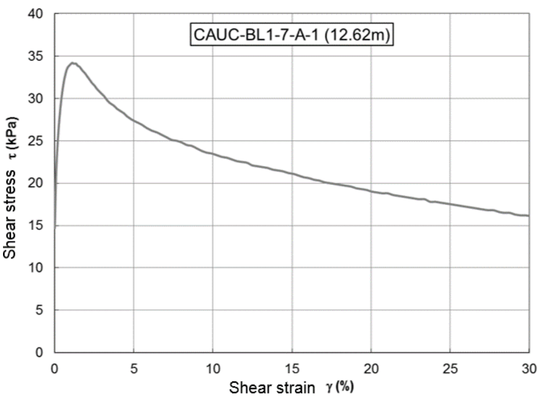

Figure 6. Example triaxial stress-strain curve for Norwegian sensitive clay

2.4 *Monte Carlo simulations*

To establish a probability distribution for the effect of including strain softening, 600 FE calculations were done with random sampling from the input parameter variables (Jostad et al., 2013). The calculations with unstable slopes were not considered when evaluating the results. The reason for this Bayesian approach (Miranda et al., 2009) is that when disregarding time effects the FoS ≥ 1 for a natural slope (Nadim et al., 2014). Results from the 474 remaining Monte Carlo simulations are shown in Figure 7, giving the factor $F_{softening}$ as defined in Figure 2 versus failure load. These data points are considered to provide a representative distribution of the possible strain softening effect in Norwegian normally to slightly over-consolidated sensitive clays in gently inclined slopes. The distribution of $F_{softening}$ is shown in Figure 8, and $[F_{softening} - 1]$ can be curve-fitted with a lognormal distribution with mean value of 0.091 and standard deviation 0.061.

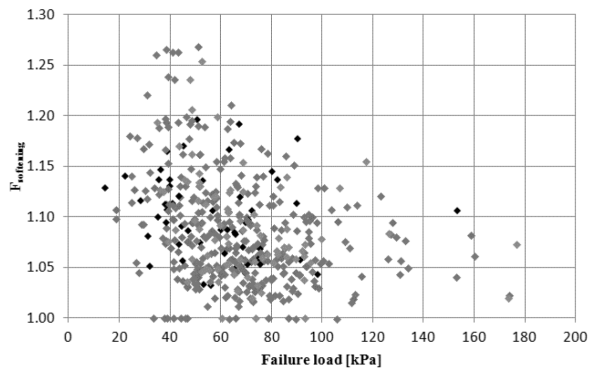

Figure 7. Scatter of reduction factor $F_{softening}$ versus failure load for 474 Monte Carlo FE simulations

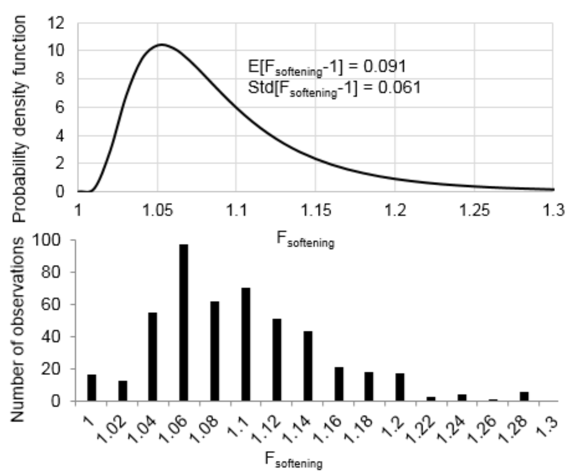

Figure 8. Distribution of factor $F_{softening}$, $E[F_{softening} - 1] = 0.091$, $Std[F_{softening} - 1] = 0.061$

3 HEADING CALIBRATION OF MATERIAL FACTOR $\gamma_M^{SOFTENING}$

To account for strain softening in design with normal limit equilibrium methods, the material factor

γ_M can be increased by a factor $F_{softening}$ to account for strain softening as follows:

$$\gamma_M^{softening} = \gamma_M \cdot F_{softening} \qquad (1)$$

Based only on the data generated in the Monte Carlo simulation in Figure 7, it is not apparent which value for $F_{softening}$ should be used in a new guideline. In a design philosophy, arguments can be made for either selecting the mean value (1.091), or a higher, more conservative value. However, an overall principle for this work was to have equal probability of failure for a perfectly plastic material and a strain softening material.

One way to achieve this is to consider a perfectly plastic design case where the spatial average undrained shear strength s_u is the only independent variable that determines failure for bearing capacity. If so, the following equations can define the probabilities of failure:

$$P_f^{perfectly\ plastic} = P(s_u < s_{u,c}/\gamma_M) \qquad (2)$$

where P is probability, su is the actual peak in-situ undrained shear strength for a perfectly plastic case, su,c is the characteristic undrained shear strength chosen in design and $\gamma_M = 1.4$ is the required material factor for non-brittle materials in Norwegian guidelines. The probability of failure $P_f^{perfectly\ plastic}$ depends on the how the characteristic strength $s_{u,c}$ is chosen compared the probability distribution of s_u and the characteristic strength $s_{u,c}$ can be chosen to obtain specific values of $P_f^{perfectly\ plastic}$.

This can be compared to the probability of failure for an equivalent design case with a strain softening material can be considered:

$$P_f^{strain\ softening} = P(s_u^{softening} < s_{u,c}/\gamma_M^{softening}) \qquad (3)$$

where $\gamma_M^{softening}$ is the required material factor for strain softening materials and $s_u^{softening}$ is the "equivalent" in-situ undrained shear strength which accounts for strain softening:

$$s_u^{softening} = s_u/F_{softening} = s_u/([F_{softening} - 1] + 1) \qquad (4)$$

where the distribution of $[F_{softening} - 1]$ is shown in Figure 8. Here the necessary increase of the material factor depends heavily on the uncertainty of the in-situ undrained shear strength s_u of the perfectly plastic material. To illustrate this, two examples were used for calibration:

Two lognormal probability distributions of s_u are shown in Figure 9 with the same mean value ($E[s_u]$ = 30 kPa), but different standard deviations ($Std[s_u]$ = 3 and 6 kPa). This correspond to a coefficient of variation CoV = 10-20 %, which can be considered typical for clay strength properties (Lacasse and Nadim, 1996).

The required increased material factor $\gamma_M^{softening}$ can be determined by running many Monte Carlo simulations of Equation 4, with random sampling from the s_u and $[F_{softening} - 1]$ distributions, Figure 9 and Figure 8 respectively. Resulting cumulative distributions from 100 000 Monte Carlo simulations are shown in Figure 10. The results can be curve fitted with a normal distribution, but also iterations can be done until the value of $\gamma_M^{softening}$ provides frequency (probability) of failure $P_f^{strain\ softening} = P_f^{perfectly\ plastic}$. This provides a better match for the low probabilities in the tail of the distribution.

Table 1 shows for the case with CoV = 10 % how $s_{u,c}$ is chosen to obtain $P_f = 10^{-2}$, 10^{-3} and 10^{-4}, the values of $\gamma_M^{softening}$ found by iteration and the corresponding $F_{softening}$. Table 2 shows the same for the case with CoV = 20 %.

For the case of low uncertainty in s_u (Table 1), a high characteristic value $s_{u,c}$ can be chosen. For example, the characteristic strength $s_{u,c}$ = 30.7 kPa, which due to the material factor $\gamma_M = 1.4$ is even higher than the mean value of s_u, is sufficient to have $P_f = 10^{-2}$. Accordingly, a high factor $F_{softening} = 1.21$ is required to account for strain softening to have the same level of safety.

For the case of high uncertainty in s_u (Table 2), a lower (more careful) characteristic value $s_{u,c}$ needs to be chosen and a lower $F_{softening}$ can be used for calibration. As the uncertainty in s_u increases, it overshadows the uncertainty of $F_{softening}$, and the required factor value converges to the mean value.

Assuming the uncertainty in todays practice is around CoV = 20% and that 1 of 1000 road fills in natural slopes fail upon construction, pragmatic values to use in guidelines for sensitive clays can be $\gamma_M^{softening}$ = 1.60 or $F_{softening}$ = 1.15. This value of $F_{softening}$ covers 88 % of the Monte Carlo FE simulations in Figure 7.

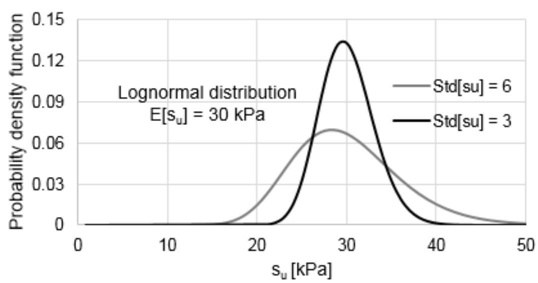

Figure 9. Example, probability density functions for two clays with different CoV

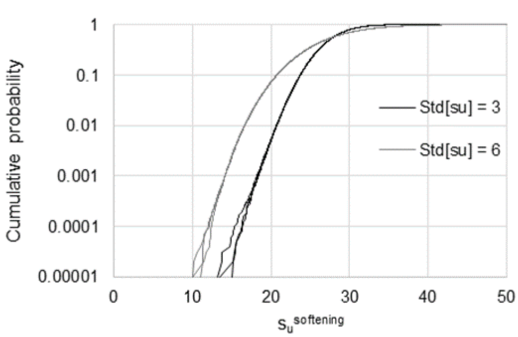

Figure 10. Cumulative distribution of $s_u^{softening}$ for 3 iterations of 100 000 Monte Carlo simulations

Table 1. Required increase from γ_M = 1.4 for $E[s_u]$ = 30 kPa, CoV = 10%

P_f	$s_{u,c}$ [kPa]	$\gamma_M^{softening}$	$F_{softening}$
10^{-2}	33.1	1.60	1.14
10^{-3}	30.7	1.69	1.21
10^{-4}	28.8	1.80	1.29

Table 2. Required increase from γ_M = 1.4 for $E[s_u]$ = 30 kPa, CoV = 20%

P_f	$s_{u,c}$ [kPa]	$\gamma_M^{softening}$	$F_{softening}$
10^{-2}	26.0	1.56	1.11
10^{-3}	22.3	1.58	1.13
10^{-4}	19.7	1.61	1.15

4 CONCLUSIONS

The results from this study will be used as a basis for establishing material factors in new guidelines. The final values depend on what is regarded as the situation of the current practice; both uncertainty in s_u and P_f in design. Another consideration is that all Norwegian marine clays include some degree of strain softening in undisturbed samples and should therefore theoretically be corrected. The current practice is that only very sensitive clays have been counted as brittle materials in the guidelines, which is found to be wrong. Also, to reduce conservatism, the required $F_{softening}$ can also be differentiated based on sensitivity analyses of the input variables, which is not presented here.

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