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Abstract	Correction factors to be used in conventional undrained stability calculations in order to account for post peak strain softening behaviour of sensitive clays, has been recommended based on an extensive sensitivity study with advanced finite element simulations. It is found that a correction of the material factor is preferred compared to a reduction of the shear strength. The input parameters to the sensitivity study that had the highest correlation with the required correction factor were the shear strength increase with depth and the brittleness, which is the rate of shear strength reduction with strain. In a large block sample database of sensitive Norwegian clays, there was no clear correlation between the brittleness and the sensitivity. Hence, classification of the clays based on the sensitivity is not recommended for evaluating the effect of strain softening on the capacity.	

Chapter 20

Correction Factors for Undrained LE Analyses of Sensitive Clays

Petter Fornes and Hans Petter Jostad

Abstract Correction factors to be used in conventional undrained stability calculations in order to account for post peak strain softening behaviour of sensitive clays, has been recommended based on an extensive sensitivity study with advanced finite element simulations. It is found that a correction of the material factor is preferred compared to a reduction of the shear strength. The input parameters to the sensitivity study that had the highest correlation with the required correction factor were the shear strength increase with depth and the brittleness, which is the rate of shear strength reduction with strain. In a large block sample database of sensitive Norwegian clays, there was no clear correlation between the brittleness and the sensitivity. Hence, classification of the clays based on the sensitivity is not recommended for evaluating the effect of strain softening on the capacity.

20.1 Introduction

In sensitive clays progressive failure mechanisms may develop due to strain softening behavior, i.e. where the undrained shear strength after a peak value reduces significantly with growing shear strain as shown in Fig. 20.1. In Norway, slope stability analyses are generally performed by limit equilibrium methods (LEM). However, these methods cannot directly account for the strain softening behaviour of sensitive clays, since the peak strength will not be fully mobilized along the shear surface. In the past, the peak undrained shear strengths used in LEM analyses were generally underestimated due to sample disturbance when using 54 mm soil sampler (also shown in Fig. 20.1). Today, the undrained shear strength is more often based on triaxial tests on high quality block samples. Therefore, in order to not overestimate

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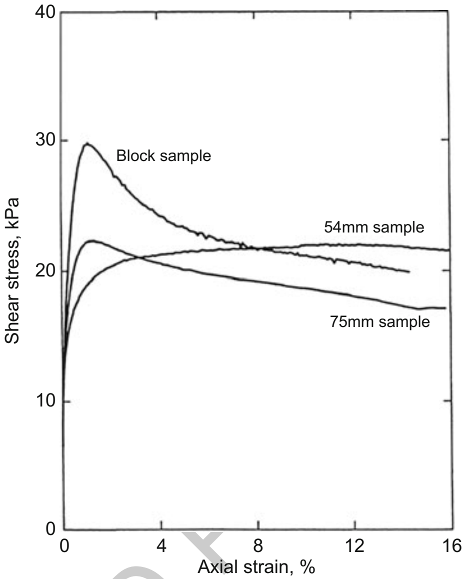

Fig. 20.1 Example of increased peak undrained shear strength and increased rate of softening from block samples on a soft low plastic Norwegian clay (Lunne et al. 1997)

the safety margin when taking advantage of the higher peak shear strength, one need to also account for the effect of strain softening behaviour generally observed for these materials.

In a research and development project sponsored by NIFS (www.naturfare.no), an extensive Finite Element Method (FEM) sensitivity study was performed in order to quantify the effect of strain softening behaviour on the bearing capacity of sensitive Norwegian clays (Jostad et al. 2014). It is concluded that a pragmatic solution may be to use an increased material factor if conventional LEM is used on strain softening brittle clays (NGI 2014). The material factor increase should aim to maintain more or less the same average safety level compared to the current design practice based on 54 mm samples.

20.2 Correction of the Material Factor

The effect of strain softening when calculating the stability with conventional LEM, could either be accounted for by reducing the undrained shear strength or increasing the required material factor. However, based on results from the advanced finite element analyses, it is found that the failure mechanism is rather complex since the peak load corresponds to an instability condition. The effect of the reduced capacity is therefore difficult to capture by only reducing the shear strength of the strain softening material. Also the effect that the passive zone is not fully mobilized at this state reduces the capacity. An increase of the required material factor also agrees with the current practice proposed in NPRA (2014) where the material factor

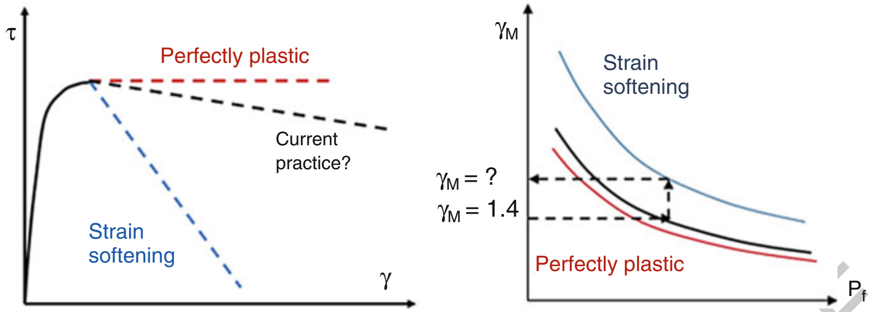

Fig. 20.2 Illustration of a perfectly plastic and a strain softening material behaviour. The current practice accepts some higher probability of failure P_f for materials that show a modest strain softening behavior

should be increased by about 7% in order to account for a brittle material response. Therefore, in this study the effect of strain softening is accounted for by:

$$\gamma_M^{\text{softening}} = \gamma_M \cdot F_{\text{softening}}$$

where γ_M is the material factor calculated by LEM based on the peak undrained shear strength, and $F_{\text{softening}}$ is the necessary correction in order to account for the reduced capacity obtained by a corresponding finite element analyses (FEA) using Plaxis (www.plaxis.nl) and the material model NGI-ADPSoft that includes the effect of post peak strain softening behaviour (Grimstad and Jostad 2010, 2011).

Ideally, the recommended design practice should give the same probability of failure for materials with or without strain softening behaviour. If a material factor γ_M results in an accepted safety level for a perfectly plastic material, the recommended material factor for a strain softening material should then be higher when the capacity is calculated with the same LEM. This is illustrated in Fig. 20.2.

20.3 Sensitivity Study

An extensive sensitivity study including about 500 finite element analyses including direct modelling of typical strain softening behaviour of Norwegian sensitive clays was performed in order to quantify the effect of strain softening on the calculated capacity. An embankment for a new road in a gently inclined very long slope of mainly sensitive clay covered by a non-sensitive clay (dry crust) was considered as an appropriate problem case (NGI 2012). A representative range of input parameters, including the post-peak behavior, was based on results from laboratory tests on high quality block samples from different locations with sensitive clays in Norway (Karlsrud and Hernandez-Martinez 2013). The parameter set for each simulation was then established by sampling randomly from the distributions by the Monte Carlo method.

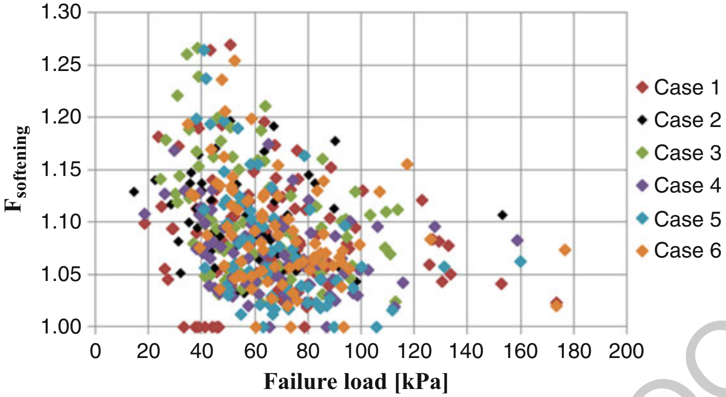

Fig. 20.3 Correction factor $F_{softening}$ to account for strain softening in a perfectly plastic stability calculation, versus failure load for different cases of input parameters. Cases 1–6 are based on different geometrical parameters (Jostad et al. 2014)

For each parameter set, the maximum height of the embankment was determined by applying a distributed vertical load representing the weight of the fill. The maximum load that could be applied is the load capacity. The correction factor $F_{softening}$ was found by a corresponding simulation without post-peak softening, where the peak undrained shear strength was reduced by a factor until the load capacity was equal to the simulation with softening. These analyses were described in a paper to IWLSC in 2013 (Jostad et al. 2014).

The calculated correction factors in this study varied between 1.0 and 1.3, with a mean value of 1.09 and a standard deviation of 0.06, as shown in Fig. 20.3. This means that in a stability analysis using conventional LEM (without the effect of softening) and an undrained shear strength based on the peak strength from high quality block samples, the capacity may be overestimated by as much as 30%. One simple way of accounting for this shortcoming is to increase the required material factor γ_M by 30%.

20.4 Correction Factor for Different Input Parameters

Increasing the required material factor for all cases involving sensitive clays by 30% will be very conservative, i.e. with a safety level higher than the present design practice. To avoid this, the large range of correction factors presented in Fig. 20.3 are divided into groups depending on the input data, so that the correction factor can be related to specific sets of material parameters.

20.4.1 Correlations with Input Parameters

In order to identify which parameters give the largest correction factor, the correlation between the correction factor and the different input parameters was studied, see NGI (2012) and Fornes and Jostad (2013). It was found that the parameters that govern the shear strength increase with depth had the largest effect on the magnitude of the correction factor. In this study, the undrained shear strength profile is defined by y_{ref} that gives the depth where the shear strength starts to increase significantly with depth, see Fig. 20.4. Then, the idealized linear increase in shear strength with depth is given by $s_u{}^A{}_{inc}$. The correction factor $F_{softening}$ increases with increasing y_{ref} and with decreasing $s_u{}^A{}_{inc}$.

The reason why the shear strength profile affects the effect of softening, is that the maximum load (capacity) in these cases occurs before a fully developed failure mechanism is obtained. At this point of instability, the reduction in resistance in the zones that experience softening (reduction in shear strength) is exactly balanced by the increase in resistance in the remaining soil volume upon further deformation. After this instability point, the propagation of the failure zone (also often called shear band) which generally starts from the loaded area, continue to propagate downwards however with a gradually reducing driving force, see Fig. 20.5. Therefore, a case with a shear strength that increases with depth will delay the point where the system becomes instable. This means that the shear band has propagated longer and the critical point is closer to the condition with a fully developed failure mechanism. If the failure mechanism is fully developed when the peak load is reached, the correction factor becomes equal to 1.0. A high correction factor is obtained if the instability point occurs close to the condition where the first point in the soil has reached the peak shear strength.

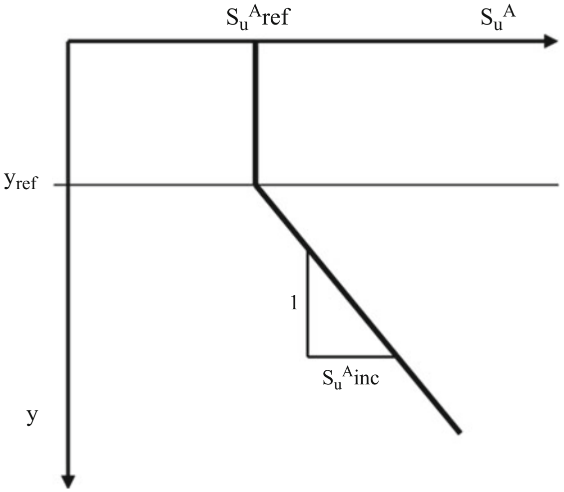

Fig. 20.4 Shear strength profile defined by y_{ref}, $s_u{}^A{}_{ref}$ and $s_u{}^A{}_{inc}$

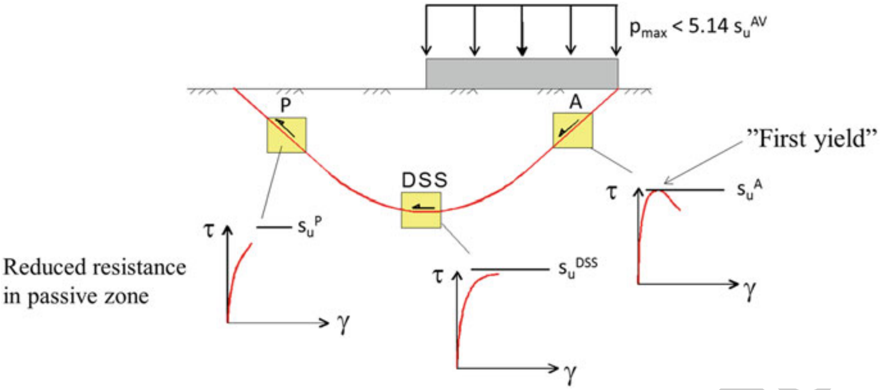

Fig. 20.5 Peak load at an instability point where the reduction in resistance due to softening is exactly equal to the increase in resistance in the remaining soil upon further deformation

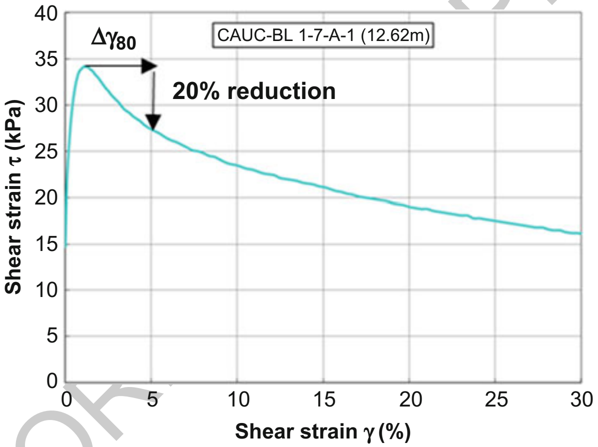

Fig. 20.6 The brittleness is here defined by the parameter $\Delta\gamma_{80}$, which is the additional shear strain necessary to reduce the active peak undrained shear strength by 20–80%

The brittleness of the clay may be defined by how much additional strain is necessary in order to reduce the peak shear strength by a given amount (percent). Since this parameter controls the post peak softening behaviour, it affects the correction factor. In this study, the brittleness is controlled by a parameter $\Delta\gamma_{80}$, defined as the additional shear strain necessary to apply in order to reduce the peak undrained shear strength in a triaxial CAUA-test by 20–80% as illustrated in Fig. 20.6. Low values of $\Delta\gamma_{80}$ corresponds to high brittleness, and thus a more rapid reduction in the resistance in the zones with softening. Thus, also an instability point closer to the point of "first yield". The selection of reduction to 80% of the

Table 20.1 Mean value and standard deviation of $F_{softening}$ for the 27 input parameter groups

		Mean value and standard deviation of $F_{softening}$		
$\Delta\gamma_{80}$	$s_u{}^A{}_{inc}$	$y_{ref} = 0–2$ m	$y_{ref} = 2–4$ m	$y_{ref} > 4$ m
0–2%	2–3.5 kPa/m	1.059 ± 0.020	1.125 ± 0.044	1.164 ± 0.055
	3.5–5 kPa/m	1.041 ± 0.021	1.083 ± 0.035	1.138 ± 0.038
	>5 kPa/m	1.021 ± 0.023	1.057 ± 0.023	1.107 ± 0.017
2–5%	2–3.5 kPa/m	1.062 ± 0.027	1.111 ± 0.041	1.167 ± 0.058
	3.5–5 kPa/m	1.041 ± 0.020	1.066 ± 0.029	1.110 ± 0.040
	>5 kPa/m	1.024 ± 0.006	1.046 ± 0.025	1.081 ± 0.026
> 5%	2–3.5 kPa/m	1.000[a]	1.070 ± 0.026	1.138 ± 0.046
	3.5–5 kPa/m	1.030 ± 0.021	1.045 ± 0.012	1.104 ± 0.052
	>5 kPa/m	1.019[a]	1.042 ± 0.013	1.045

[a] Only one data point

peak shear strength is based on the results from the finite element analyses, where this value is found to be typical when the peak load is reached.

20.4.2 *Correction Factors Based on Ranges of the Most Important Input Parameters*

In order to relate the correction factor to specific values of input parameters, the results from the sensitivity study were grouped based on the three most important parameters ($\Delta\gamma_{80}$, y_{ref} and $s_u{}^A{}_{inc}$). Brittleness parameter $\Delta\gamma_{80}$ was divided into values from [0–2%], [2–5%] and [>5%]. Reference depth y_{ref} was divided into values from [0–2 m], [2–4 m] and [>4 m]. Incremental shear strength $s_u{}^A{}_{inc}$ was divided into values from [2–3.5 kPa/m], [3.5–5 kPa/m] and [>5 kPa/m]. This gave in total 27 different groups of input parameters, further documented in NGI (2014). The mean value and standard deviation of $F_{softening}$ within each of these 27 groups are presented in Table 20.1. An example of the distribution of the correction factor $F_{softening}$ is shown in Fig. 20.7 for groups with high brittleness and low shear strength increase with depth.

20.4.3 *Correlations Between Brittleness Parameter $\Delta\gamma_{80}$ and Index Data*

To study possible correlations between standard index data and the brittleness parameter $\Delta\gamma_{80}$, in order to replace this parameter with a more common soil parameter, NGI's block sample data base (Karlsrud and Hernandez-Martinez

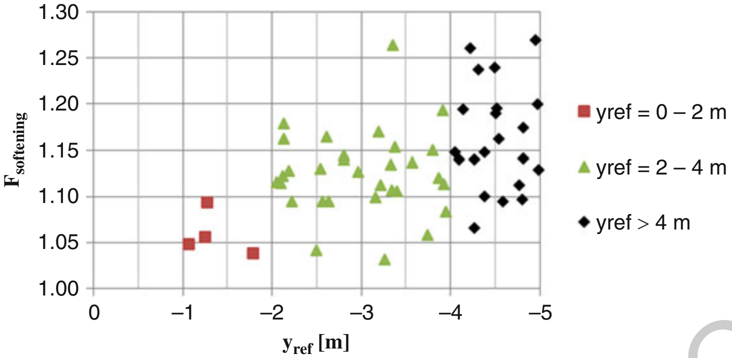

Fig. 20.7 Correction factor $F_{softening}$ versus reference depth y_{ref} for cases with high brittleness ($\Delta\gamma_{80} = 0$–2%) and low shear strength increase with depth ($s_u{}^A{}_{inc} = 2$–3.5 kPa/m) (NGI 2014).

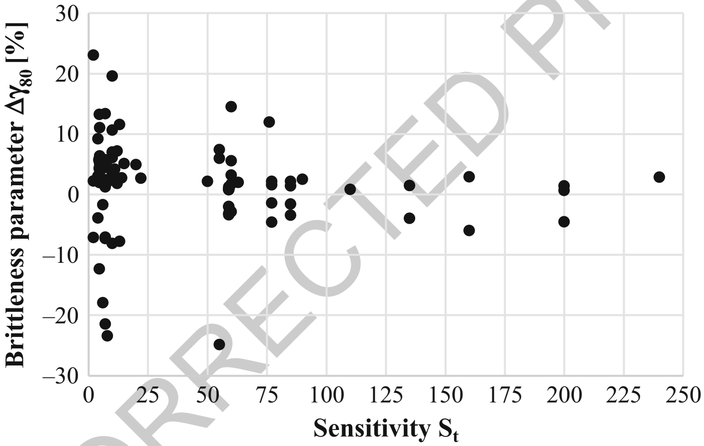

Fig. 20.8 Correlation between brittleness parameter $\Delta\gamma_{80}$ and sensitivity S_t. Negative values are from passive triaxial tests

2013) was investigated. The following parameters were considered: sensitivity S_t, remoulded undrained shear strength s_{ur}, over-consolidation ratio OCR, water content w, plasticity index I_p, liquidity index IL and sample depth.

No clear correlation was found between the brittleness parameter $\Delta\gamma_{80}$ and the index data. High sensitivity and high IL are clear indications of high brittleness. However, low values may still give high brittleness as shown for sensitivity S_t in Fig. 2.08.

Based on this study, it is therefore concluded that one should be very careful to use sensitivity or other index data to estimate the potential brittleness of sensitive clays that effects the capacity. The only reliable information is results from CAUC tests on high quality block samples.

20.5 Adjustment Based on Current Design Practice

All Norwegian sensitive clays show some degree of strain softening behaviour, which means that the capacity is lower than for a perfectly plastic material. The current practice and regulations for sensitive clays in Norway are described by Oset et al. (2014). Based on recommendations in NPRA (2014) and NVE (2014), it is typically only the soils classified as brittle or with high sensitivity that are corrected due to this strain softening behavior. In NVE (2014), brittle clays are defined by $S_t > 15$. However, as shown in this study, less sensitive clays ($S_t < 15$) may still be brittle based on $\Delta\gamma_{80}$ (as shown in Fig. 2.08) and require a high correction factor. This means that some reduction in the capacity compared to a perfectly plastic material is accepted in the current design practice. Therefore, in order not to increase the safety level significantly (with a corresponding increase in costs during developments of new infrastructure), it is estimated how much of the correction factor has been included in the current practice.

A simple approach was to assume that sensitive clays which are in the lowest degree of brittleness category according to the definition used here ($\Delta\gamma_{80} > 5\%$), are accepted to not be adjusted (correction factor 1.0). Only the relative part of the calculated correction factor is then proposed to be used. Figure 20.9 illustrates this approach for the cases with high brittleness and low shear strength increase with depth.

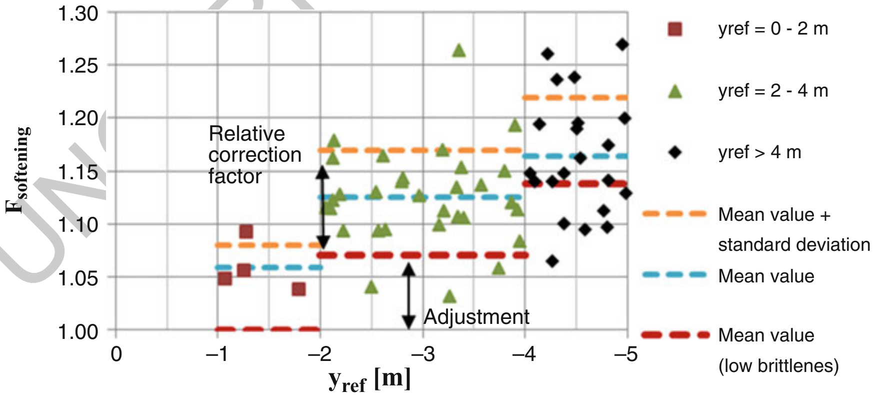

Fig. 20.9 Adjustment of correction factor, for high brittleness and low shear strength increase with depth. The *red dashed line* shows the mean value for the corresponding less brittle clays

Table 20.2 Recommended correction factor $F_{softening}$ for high and medium brittle clays

	$F_{softening}$ for high and medium brittleness ($\Delta\gamma_{80} = 0$–5%)		
$s_u{}^A{}_{inc}$	$y_{ref} = 0$–2 m	$y_{ref} = 2$–4 m	$y_{ref} > 4$ m
2–3.5 kPa/m	1.10	1.10	1.15[a]
3.5–5 kPa/m	1.05	1.10	1.10
>5 kPa/m	1.05	1.05	1.10

[a] Increased from 1.10 in order to account for that current practice most likely give higher probability of failure for these cases

20.6 Recommended Correction Factors for Sensitive Clays

The sensitivity study shows some variations in the calculated correction factor. The actual value to use in order to give the accepted probability of failure depends therefore also on the uncertainties in the peak shear strength. If the uncertainty in the peak shear strength is high, the accepted probability of failure could be satisfied by using the mean value of the correction factor as shown in Fornes and Jostad (2015). For rather typical uncertainties in the peak undrained shear strength, a mean value plus one standard deviation of the correction factor can give approximately the same probability of failure.

Table 20.2 provides recommended correction factors for the high ($\Delta\gamma_{80} = 0$–2%) and medium ($\Delta\gamma_{80} = 2$–5%) brittle clays. The values are equal to the mean value plus one standard deviation from Table 20.1, minus the mean value for the less brittle clays ($\Delta\gamma_{80} > 5\%$) in the corresponding parameter groups, and then rounded up to the closest increment of 0.05. In this way, the same values were obtained for both high and medium brittle clays. The values in the [$s_u{}^A{}_{inc} = 2$–3.5 kPa/m and $y_{ref} > 4$ m] group are further increased from 1.10 to 1.15, in order to account for that these shear strength profiles can be expected to have relatively large probability of failure in the current practice.

20.7 Conclusions

The effect of strain softening behaviour of typical Norwegian sensitive clays is quantified in an extensive sensitivity study by advanced finite element analyses. Based on this study, correction factors are proposed for increasing the required material factor when the stability analysis is performed by standard limit equilibrium methods (LEM). These factors are first of all meant for cases where the undrained shear strength is obtained from triaxial tests on high quality block samples and conditions with rapidly increasing driving loads. Different correction factors are proposed depending on the actual brittleness of the material and the shape of the idealized shear strength profile with depth. To use the index parameter sensitivity, S_t, to estimate the brittleness of sensitive clays is not recommended, since even less sensitive clay ($S_t < 15$) also may show very brittle post peak strain softening behaviour. The recommended values are suggested in order to keep the safety level on the same level as used in the current design practice, to not increase the costs of new developments.

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