Stability analyses of quick clay using FEM and an anisotropic strain softening model with internal length scale

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ABSTRACT
Sensitive soft clays generally display a significant post peak strain softening response under undrained deformation. A consequence of this behavior is that the safety factor during undrained stress changes cannot be calculated by conventional limiting equilibrium methods and when using numerical methods as the finite element method the solution is mesh dependent. In finite element analyses a shear band generally develops in the strain-softening regime. However, without a proper regularization technique the thickness and generally also the orientation of the shear band are governed by the finite element discretization. To overcome this problem of mesh dependency an internal length scale, that controls the shear band thickness without prescribing the orientation, must be introduced. One method is to use the non-local strain approach. This approach may be implemented into any non-linear finite element programs without reformulating the governing finite element equations. In this paper the NGI-ADPSoft model with a non-local strain approach is used to investigate the stability of a filling in a quick clay slope. The case studied is a slope at Vestfossen that failed due to construction work 11th of September 1984. The slide involved approximately 150 thousand m^3, where the terrain in the backside of the slide was lowered with about 5 meters. The back-calculation of the construction of the fill and the following slide event was done using a large deformation finite element analysis with the PLAXIS 2D code.

Keywords: Slope stability, FEM, softening, regularization

1 INTRODUCTION

In the Norwegian national amendment to Eurocode 7 (2008) it is stated in table NA.A.4 that the partial factor should be increased beyond the given value when progressive failure is possible. However, it does not say how much it should increase. By studying historical slide events and other design projects it is clear that it is uncertainties in how to account progressive type of failure in respect to the required safety level. As an example to this, NVE (2011) and SVV (2010) give different requirements.

Grimstad and Jostad (2011) give a description of a model and procedures that could be used for analyses of stability in quick clay areas. This article is partly based on the same content as in Grimstad and Jostad (2011). However, it is focusing more on the back-calculation of the Vestfossen slide from 1984. In addition it describes a procedure that may be used to establish correction factors that account for the effect of strain softening in analyses with perfectly plastic materials.

1.1 Current practice – Limit equilibrium

Current practice in stability calculations for fills, cuts and slopes in areas with quick clay is to use the limit equilibrium method. For undrained (total stress) analyses, the well-known Fellenius method is used in conjunction with the assumption of perfectly plastic behavior. In addition to these circular slip surfaces combined surfaces are also sometimes checked. The practice at NGI is that the anisotropy in undrained shear strength is included in the analyses. Also in some cases softening is partly accounted for by assuming strain compatibility along the critical circle. This is in most cases done by manually reducing the undrained shear strength in compression and for direct simple shear by some percentage. It is also clear that limit equilibrium methods have some advantages over the finite element method:

- It gives factor of safety for more than the most critical failure mode
- It is possible to check the effect of a countermeasure on any mechanism, which is required in current guidelines (i.e. SVV 2010).

In some cases the 2D finite element method is used to evaluate the initial stress condition (in conjunction with the first yield concept) or for control on factor of safety for combined surfaces. It is well known that the failure mechanism in strain softening clays has a different character than for a failure mechanism in perfectly plastic clays (Janbu, 1970, Bernander 2000 and 2011, Andresen at al. 2002, Andresen and Jostad 2004 and 2007).

1.2 Finite element method and material model for quick clay

During the last 10 years, NGI and others have developed material models and programs that can be used for calculation of progressive failure in strain softening clay. (Andresen at al. 2002, 2006, Grimstad et al. 2010 and Grimstad and Jostad 2011) Fundamental aspects with the method are:

- Compatibility in displacements and corresponding strains
- Equilibrium between driving forces and stabilizing stresses
- Relationship between strains and stabilizing stresses including reductions in the undrained shear strength beyond the strain at peak shear strength given by an anisotropic elastoplastic material model e.g. NGI-ADPSoft (Grimstad et al. 2010)
- Regularization of the finite element calculation by using so called "non-local" strain.
- Large deformation formulation

The NGI-ADPSoft model is a total stress based model that takes into account the anisotropy in behavior under undrained shearing dependent on strain condition. The model uses input from triaxial compression tests (s_u^C, $s_u{}^C{}_r$, $\gamma_p{}^C$, $\gamma_r{}^C$), direct simple shear tests (s_u^{DSS}, $s_u{}^{DSS}{}_r$, $\gamma_p{}^{DSS}$, $\gamma_r{}^{DSS}$) and triaxial extension tests (s_u^E, $s_u{}^E{}_r$, $\gamma_p{}^E$, $\gamma_r{}^E$). Where s_u stands for undrained shear strength, *p* for peak, *r* for residual, γ for shear strain, *C* or *A* for compression or active in case of plane strain condition, *DSS* for direct simple shear and *E* or *P* for extension or passive in case of plane strain condition. The model also needs input of the initial stress condition, initial shear mobilization and elastic shear stiffness.

1.3 Regularization

A problem with using a constitutive model that includes softening is that the results generally become mesh dependent. This means that repeated refinement of the finite element mesh gives increasing brittleness. By replacing the plastic (permanent) strain in a Gauss point with a non-local strain (i.e. a weighted strain over the neighboring Gauss points) the results become dependent on the deformation in a specific area rather than dependent on the element size. More details on this can be found in Brinkgreve (1994).

2 CASE STUDY – VESTFOSSEN (1984)

2.1 Background

Progressive failure can be divided into several types. One of this is the downward progressive failure, which is typically triggered by loading at the top of the slope (at least at top of the initial failure mechanism). Table 1 gives an overview of some failures in natural slopes that are most likely triggered by such a fill.

The idea in this paper is to use such a slide to quantify the effect of softening. Due to uncertainties in underlying data the slide with most relevant information was used for this purpose. Figure 1 shows the extent of the failure at Vestfossen, 11th of September 1984.

Table 1 Some possible downwards progressive failures in Norway

	Year	L [m]	A [m^2]	V [m^3]
Bekkelaget	1953	160	16E3	100E3
Sem	1974	120		
Vestfossen	1984	150	15E3	150E3
Balsfjord	1988		45E3	450E3
Leistad	2002		25E3	
Smårød	2006	230	100E3	

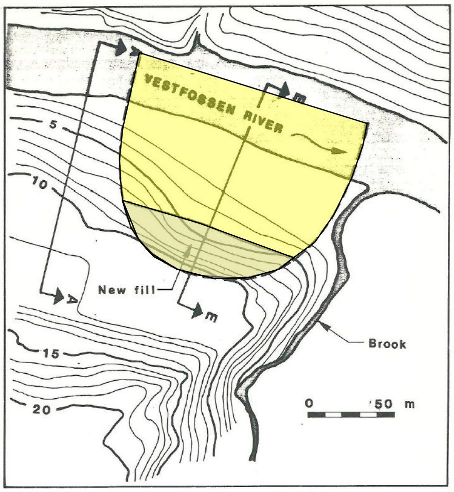

Figure 1 Extent of the 1984 slide at Vestfossen

2.2 Material parameters

NGI (1984) give suggested profiles for undrained shear strength based on vane shear tests. Undrained triaxial compression and direct simple shear tests were also carried out. These results are extrapolated along the profile by using the SHANSEP procedure (Ladd and Foot, 1974).

$$s_u = \sigma'_{v0} \cdot S \cdot \left(1 + \frac{POP}{\sigma'_{v0}}\right)^m \cdot OCR_\tau{}^m \qquad (1)$$

Where the undrained shear strength, s_u, is made anisotropic by using different S and m values dependent on direction of shearing. S is the SHANSEP normalizer, m is the SHANSEP exponent, POP is the geological pre-loading pressure, OCR_τ is the degree of over consolidation due to creep and σ_{v0}' is the initial vertical effective stress.

Data in Karslrud (2010) is used to find values for S and m as functions of the water content.

By assuming the location of the original seabed, strength profiles (Figure 3) are established. Profile for s_u^A is given in Figure 4. Since SHANSEP gives an undrained shear strength that is approaching zero towards the surface, a minimum value of about 30 kPa was set for the s_u^A value. The vane shear tests give support for this cut.

2.3 Limit equilibrium calculations

Limit equilibrium calculations are done both with and without the assumption of strain compatibility. Strain compatibility is achieved by searching for the shear strain that maximize the factor of safety for a given circular failure surface. This means that the most critical surface is not necessary the same as the one found from classical limit equilibrium calculation. The stress-strain curves including the post peak strain softening behavior have to be given in order to use strain compatibility. In this case slightly idealized laboratory results from NGI (1982) were used (Figure 2). Figure 5 gives the factor of safety and the critical slip surface prior to filling. Figure 6 gives the situation after filling for the case when the fill is considered as driving. When the filling is considered as stabilizing the factor of safety is calculated to be 1.38 and 1.30 without and with strain compatibility, respectively. As can be seen from the calculated factors of safety the effect of strain compatibility is in the order of 6-8%. Furthermore, when the fill is considered to be driving the factor of safety is very low.

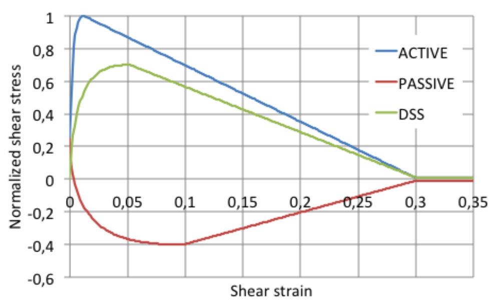

Figure 2 idealized laboratory results used in LE strain compatibility calculations

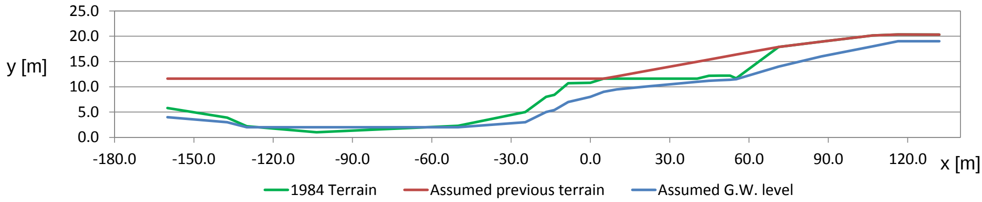

Figure 3 Profile for terrain prior to fill in 1984, assumed historic terrain (seabed) and assumed ground water level prior to filling

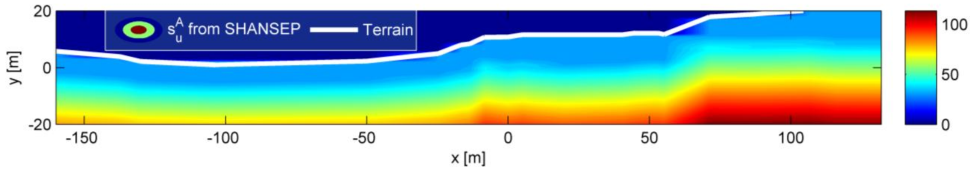

Figure 4 Profile over calculated s_u^A [kPa] for Vestfossen

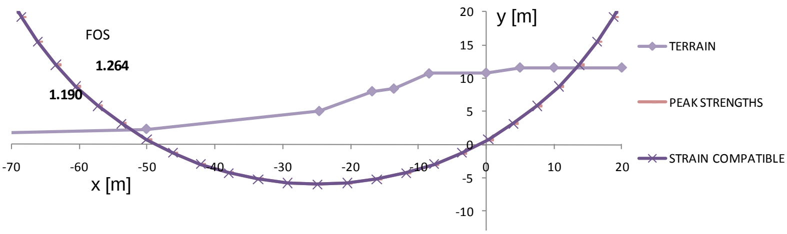

Figure 5 Initial critical mechanisms prior to filling

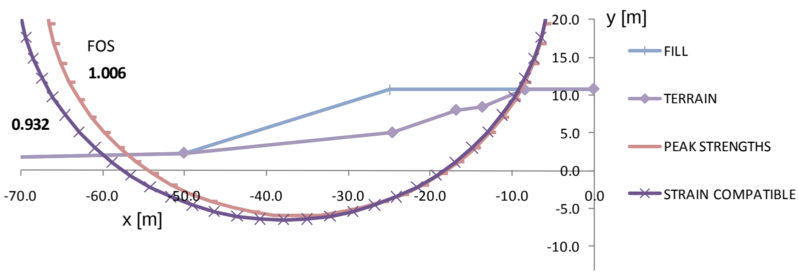

Figure 6 Mechanisms with the fill on the driving side

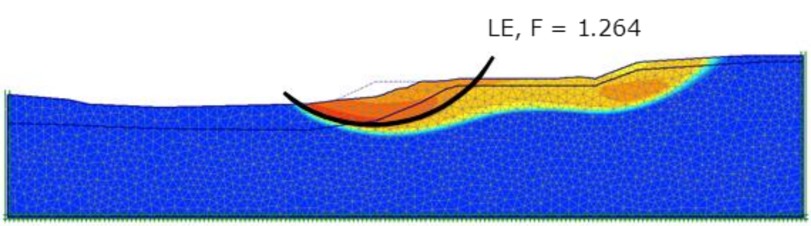

Figure 7 Calculated perfectly plastic failure mechanism (total deformation, scale not important) in PLAXIS before filling, F = 1.28, including critical slip surface from limit equilibrium analysis

2.4 Finite element calculations

As a reference, a calculation with the perfectly plastic version of the NGI-ADP model was made. The input to the model was done using a special version allowing for input of parameters per Gauss point. The finite element program PLAXIS (www.plaxis.nl) was used with c-phi reduction. Figure 7 gives the results from the finite element analysis. The result compares well with the limit equilibrium analysis. After this analysis the filling was modeled using the NGI-ADPSoft model with "non-local" strain and large deformation. The heave on the passive side gave a significant "local" stabilizing effect, forcing the failure to continue to propagate horizontally toward the river. Figure 8 shows the calculated vertical displacements at the end of the analysis on the measured final configuration of the slope.

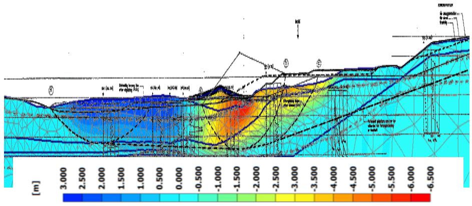

Figure 8 Plot of calculated vertical displacement at end of the analysis on the measured final configuration of the slope (Note that the vertical axis is scaled)

3 PROBABILITY ASSESSMENT

Finite element calculation with softening is generally not used in design as it has some practical limitations. For instance it does not give a factor of safety, only a failure load. However by consider the factor of safety as 1.0 for this failure load, a reduction factor between perfectly plastic material behavior and strain softening behavior can be found. The failure load is then applied in a phi-c reduction analysis with the perfectly plastic material. This analysis will give a factor of safety larger than 1.0. This factor may be used as a correction factor, however, only valid for this case. In order to objectively find a correction factor that can be used for other cases, a special calibration program, that automizes these calculations has been developed. Analyses with varying input using the Monte Carlo principle (Metropolis and Ulam, 1949) may then be performed. Figure 9 gives result of such an analysis for a bearing capacity problem of an embedded foundation. In the example 30 analyses with varying input using uniform, triangular, normal and log-normal distributions for the parameters were used. For a given confidence level a reduction factor valid for this case can be established.

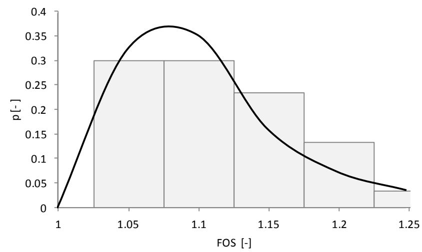

Figure 9 Result from a test calibration analysis

In the future this method will be applied to different slope configurations such that an advice on a correction factor that can be used in design can be given.

4 CONCLUDING REMARKS

This article demonstrates the effect of softening in back-calculation of the quick clay slide at Vestfossen in 1984. The slide was initiated by construction of a fill in the lower part of the slope. The SHANSEP procedure was used to extrapolate the undrained strength parameters along the slope. Limit equilibrium analyses were used to show that the calculated factor of safety with the fill as a driving force was low. The progressive failure, that happened after the initial instability initiated by the fill, propagated almost 100 m into a horizontal terrain. A finite element calculation with the NGI-ADPSoft model with non-local strain and large deformations was used to simulate the progressive failure event. Good agreements with the measured behavior were obtained. Finally the article presents a procedure for establishing a correction factor for softening to be used in factor of safety analyses with a perfectly plastic material. Results from some trial simulations of a bearing capacity problem shows that such analyses are feasible. In the future the procedure will be used on several cases, both historical and hypothetical in order to give advises for such a correction factor.

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