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Mapping the 3D effect for slope stability analyses of quick clay slopes

Cartographie de l'effet 3D pour les analyses de stabilité des pentes en argile rapide

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ABSTRACT: Industry quite often utilizes 2D limit equilibrium analyses to check the stability of sensitive and quick clay slopes. However, such analyses fail to capture the post peak reduction in undrained shear strength of these clays. In this work, finite element modelling with an appropriate constitutive model, capable of capturing strain softening, was used to compare 2D analyses against 3D analyses. Different slope widths were analysed, and results demonstrated that the width of the 3D model controls the width of the failure surface and thus also the factor of safety. The effect of strain softening was studied by means of simulations with and without strain softening. To emphasise the importance of considering spatially varying undrained shear strengths for strain softening clays, results from simulations with constant undrained shear strength were compared to ones with spatially varying undrained shear strengths. The analyses were used to develop a map for 3D effect factors for various kinds of idealized slopes with varying width, slope angle/height and undrained strength profiles.

RÉSUMÉ: L'industrie utilise assez souvent des analyses d'équilibre limite en 2D pour vérifier la stabilité des pentes en argile sensible et argile rapide. Cependant, de telles analyses ne parviennent pas à capturer la réduction post-pic de la résistance au cisaillement non drainé de ces argiles. Dans ce travail, la modélisation par éléments finis avec un modèle constitutif approprié, capable de capturer l'adoucissement sous contrainte, a été utilisée pour comparer les analyses en 2D aux analyses en 3D. Différentes largeurs de pentes ont été analysées, et les résultats ont démontré que la largeur du modèle 3D contrôle la largeur de la surface de rupture et donc aussi le coefficient de sécurité. L'effet de l'adoucissement sous contrainte a été étudié au moyen de simulations avec et sans adoucissement sous contrainte. Pour souligner l'importance de la prise en compte des résistances au cisaillement non drainé variant spatialement pour les argiles subissant un adoucissement sous contrainte, les résultats des simulations avec une résistance au cisaillement non drainé constante ont été comparés à ceux avec des résistances au cisaillement non drainé variant spatialement. Les analyses ont été utilisées pour élaborer une carte des facteurs d'effet en 3D pour divers types de pentes idéalisées avec une largeur variable, un angle/une hauteur de pente et des profils de résistance au cisaillement non drainé variables.

Keywords Quick clay; landslide; softening; 3D FEM.

1 INTRODUCTION

Soft sensitive clays like Norwegian quick clays undergo strain-softening under undrained loading, posing risks of catastrophic failure in slopes. Accurate modelling of slope stability (safety factor) is crucial. The progressive failure mechanism in strain-softening clays may reduce stability compared to non-softening materials with the same peak undrained shear strength. While two-dimensional studies explored the reduction (Fornes & Jostad, 2017 suggested 20%, Rødvand et al., 2022 found no significant reduction), the impact in three dimensions remains unclear. Current two-dimensional analyses don't fully represent the true three-dimensional nature of slope stability, and the effect of strain softening in three dimensions is not well-understood. This work aims to quantify strain-softening effects on three-dimensional stability using PLAXIS 3D V21 and the NGI-ADPSoft model for quick clay softening behaviour.

2 NUMERICAL & CONSTITUTIVE MODEL

This section describes the methodology employed in creation of the 3D quick clay slope model in PLAXIS

3D. The choice of constitutive model to capture the behaviour of the quick clay is explained.

2.1 Numerical model of slope

PLAXIS 3D V21 (2021) facilitated the creation and analysis of the 3D boundary value problem (BVP), referred to as the model. The model utilized 10-noded tetrahedral elements with second-order interpolation for displacements. Figure 1 outlines the dimensions of the 3D quick clay slope model, meshed with fully fixed bottom and laterally fixed boundaries against horizontal movement. The slope width (W) varied (H, 2H, 3H, 6H) to evaluate 3D effects, while the slope height (H) remained constant at 50 m. Note that Figure 1 models only half the slope width, exploiting symmetry. Although slope and clay layer depth influence 3D effects, this work concentrates on softening behaviour, maintaining constant depth and slope inclination for consistency. Once a trend is established for the selected slope geometry, previous work (Jostad & Lacasse, 2015) suggests that the same trend would extrapolate to other slope angles and depths.

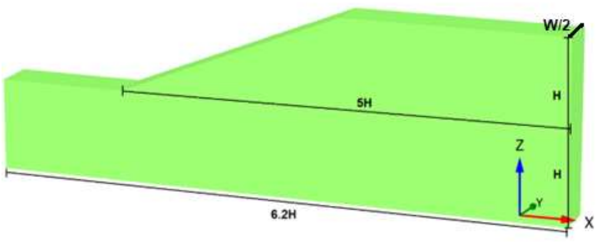

Figure 1. PLAXIS 3D model of the idealised quick clay slope.

2.2 Constitutive model: NGI-ADP Soft

NGI-ADP, an elastoplastic anisotropic shear strength-based model (Grimstad et al., 2012; PLAXIS V21, 2021), is used for capacity, deformation, and soil-structure interaction analyses under undrained loading of clay. It incorporates anisotropy based on the ADP framework (Bjerrum, 1973), where "A" is active, "D" is direct shear, and "P" is passive. Formulated for 3D stress states, NGI-ADP aligns undrained failure shear strengths and strains with experimental results, employing a translated Tresca criterion (Grimstad et al., 2012) and elliptical interpolation. With nine parameters directly obtainable from lab and in-situ testing, NGI ADP-Soft, an extension of NGI ADP, is capable of modelling undrained strain-softening behaviour, making it ideal for sensitive quick clays with distinct strain-softening beyond peak shear strength.

The focus of the work as discussed earlier was to study 3D effects in an ideal model with and without softening. Hence, material parameter values for the NGI ADP-Soft model were picked for a typical quick clay after Karlsrud's Bjerrum lecture (2010). Table 1 tabulates the material parameters; these parameters replicate the strains softening of the quick clay. Analyses conducted without softening used the same material parameters as in Table 1, barring the fact that residual strength was equal to 100 % of the peak strength. For constant undrained strength acrosss slope a value of 35 kPa was used. To study the effect of spatial variation of undrained strength on quick clay slope stability, an undrained shear strength of 20 kPa was assumed at the surface and assumed to linearly increase at a rate of 3 kPa/ unit depth.

Table 1. Material parameters used for quick clay.

Parameter		Value
Gur/su^A	Initial stiffness	300
$S_u^A ref\ (kPa)$	Reference active shear strength	35 kPa or varying with depth
s_u^{DSS} / s_u^A	Normalised DSS strength	0.59
s_u^P / s_u^A	Normalised passive strength	0.27
s_{ur}^A / s_u^A	Normalised residual active strength	0.1
	Normalised residual DSS strength	
s_{ur}^{DSS} / s_u^A	Normalised residual passive strength	0.059
s_{ur}^P / s_u^A	Shear strain at peak in triaxial compression	0.027
γ_p^C (%)	Shear strain at peak in DSS	0.6
γ_p^{DSS} (%)	Shear strain at peak in triaxial extension	0.7
γ_p^E (%)	Shear strain at residual state in triaxial compression	0.8
γ_r^C (%)	Shear strain at residual state in DSS	20
γ_r^{DSS} (%)	Shear strain at residual state in triaxial extension	20
γ_r^E (%)	Shape parameter	20
$c1$	Shape parameter	1
$c2$	Poisson's ratio, undrained conditions	1
ν_u	Total unit weight	0.495
γ_{tot} (kN/m^3)		19.5

2.3 Simulation Methodology

Failure was achieved by load increments combined with indirect displacement control using the arc length method. The standard phi/c strength reduction method cannot be used for a strain-softening material. The gravity increase method after Swan & Seo, (1999) was employed where gradually gravity loading was applied keeping other material properties constant until the slope became unstable. FoS was defined as the ratio of gravity at failure to actual gravity on earth. It was observed that shear force peaked at failure and eventually reduced as PLAXIS reduced gravity to maintain equilibrium. The analyses were continued 10 steps beyond failure, thus assuring that global failure had occurred rather than a local instability.

3 RESULTS OF NUMERICAL ANALYSIS

This section discusses in detail numerical simulation results for the ideal 3D quick clay slope. Strain softening constitutive model was used to describe the behaviour of the quick clay layer. However, no regularisation technique was used so the results would be mesh dependent. The FoS normalised by ratio of undrained shear strength to total stress at base of the slope (γH = 19.5x50 = 975), reduced as element sizes reduced as tabulated in Figure 2 and did not reach steady state indicating that results are discretisation sensitive and mesh regularisation techniques have to be employed while using a softening-based model, but this is out of scope of this work. A particular mesh discretisation was chosen and used in all the analysis to ensure consistency.

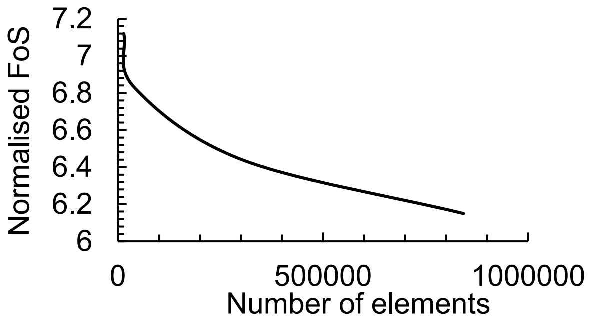

Figure 2. Effect on element size on factor of safety.

3.1 Effect of softening

The 3D model in Figure 1 simulated slope stability with and without softening effects for various widths: H (equal to slope height), 2H, 3H, and 6H, maintaining a 30 cm element size. Figure 3 displays normalized FoS for different widths, with the x-axis representing the inverse width ratio. To ensure accurate 3D effects, 2D cases were simulated in PLAXIS 3D with the same discretization error (Figure 3). The FoS decreases with wider slopes, and softening causes an 82 % drop with respect to analysis without softening. Conclusively, softening effects are comparable in 2D and 3D, consistent across varying slope widths.

3.2 3D effects with constant undrained shear strength

The model in Figure 1, featuring varied widths, maintained a constant undrained shear strength of 35 kPa across sensitive clay. Figure 4 depicts the 3D effect factor on the y-axis, representing the ratio of the factor of safety for a specific slope width to the factor of safety for a 2D plane strain model. Please note that the factor of safety at H/W=0 is 2D plane strain model factor of safety. The 3D effect factor peaked at around 90 % for narrow slopes and drops below 10 % for H/W < 0.17 (widths greater than 6H). Softening increased 3D effect factors compared to scenarios without softening. Results from PLAXIS 3D, with and without softening, are compared with Jostad and Lacasse (2015) results (b/w color scale), showing a similar trend. However, PLAXIS calculations exhibit lower 3D factors even without softening for steeper slopes (b represents the slope ratio of horizontal/vertical and d is ratio of depth to rock to height of slope, H/H here). This difference could stem from discretization variances, including the element types used in Bifurc3D and PLAXIS 3D (Zhang et al., 2013). Jostad and Lacasse (2015) used Bifurc3D, an in-house NGI development, employing isoparametric 20-noded brick elements, while PLAXIS 3D uses 10-noded tetrahedral elements.

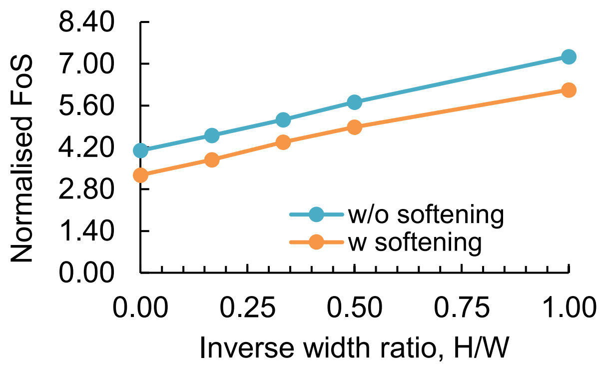

Figure 3. Variation of 3D FoS with width of slope with and without softening.

3.3 3D effects with varying undrained shear strength

To analyse the impact of varying undrained shear strength on the 3D effect factor, simulations were conducted with and without softening, where the undrained shear strength across the sensitive clay increased linearly with effective stress at a rate of 3 kPa/unit depth in m, starting at 20 kPa. Figure 5 illustrates the variation of the 3D effect factor with the inverse width ratio, showing an immediate reduction in the 3D effect as soon as a variation in undrained shear strength is considered. The case with softening exhibits higher 3D effect factors than the case without softening. A maximum 3D effect factor of 1.27 is observed for a narrow slope (H/W = 1). The 3D effect factor for a narrow slope (H/W = 1) with varying undrained shear strength with depth is 1.47 times lower than the 3D effect factor for the same slope with constant undrained shear strength. For slopes with widths larger than 6H (H/W = 0.166), the 3D effect factor with softening ranges between 1.05 and 1.07.

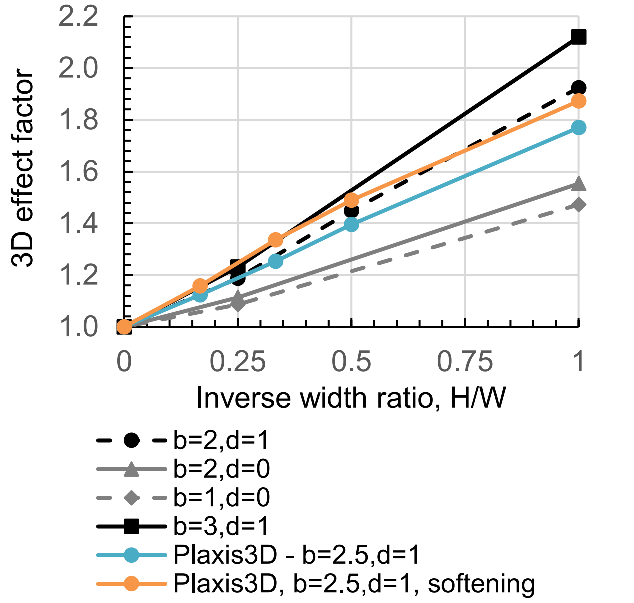

Figure 4. Variation of 3D effect factor with width of slope with and without softening for constant undrained shear strength (Jostad & Lacasse, 2015).

4 CONCLUSIONS

Wider slopes (width > 6 times height) can rely on 2D plane strain analysis due to reduced 3D effect with increasing undrained shear strength. For narrow slopes (width < 6 times height), significant 3D effects may occur, necessitating accurate 3D modeling. In cases where 3D modeling is impractical, scaling the 2D factor of safety using 3D effect factors is feasible, but attention to slope geometry is crucial. The impact of boundary conditions on softening along model edges is under study. The extent of influence is being studied by ensuring that softening to be predominant in the middle of the slope by having higher undrained strengths along slope edges.

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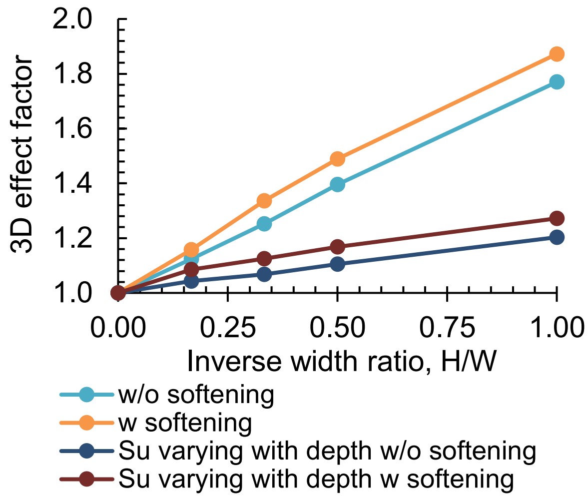

Figure 5. Variation of 3D effect factor with width of slope with and without softening for varying undrained shear strength (Jostad & Lacasse, 2015).

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