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Eurocode 7 and new design challenges using numerical methods with different soil models

Eurocode 7 et de nouveaux défis de conception en utilisant des méthodes numériques avec différents modèles de sol

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ABSTRACT According to Eurocode 7, soil strength factoring can be achieved by applying the material partial factors to the effective stress parameters c' and φ' or to the undrained shear strength c_u. Thus, in numerical analyses, material factoring is straightforward for constitutive models with c', φ' or c_u as input parameters. While designers often use simple elastic-perfectly plastic soil models for ULS checks, the use of more advanced constitutive models allows real soil behaviour to be simulated more realistically and can have significant advantages. In this paper, the feasible use of different soil models for ULS design, increasing in sophistication, such as the Mohr-Coulomb (MC), the Hardening Soil (HS), the Hardening Small Strain (HSS) and the Soft Soil (SS) models, is highlighted and better understood in the context of the EC7 requirements using deep supported excavation examples in stiff clay. The challenges of factoring undrained shear strength when using effective stress model parameters are also discussed and the effect of the soil model is investigated.

RÉSUMÉ Selon l'Eurocode 7, le coefficient de sécurité sur la capacité d'un sol peut être obtenu en appliquant les coefficients de sécurité partiels du matériau aux paramètres de contrainte effective c' et φ', ou à la résistance au cisaillement non drainée cu. Ainsi, en calcul numérique, la prise en compte du facteur de sécurité est évidente pour les modèles constitutifs requérant les paramètres d'entrée c', φ' ou cu. Alors que les concepteurs font fréquemment usage de simples modèles élastoplastiques parfaits pour les vérifications ELU (état limite ultime), l'emploi de modèles constitutifs avancés permet une simulation plus réaliste de sols réels et peut présenter des avantages significatifs. Dans cette publication, la faisabilité d'une conception ELU au moyen de différents modèles de sols plus sophistiqués tels que Mohr-Coulomb (MC), Hardening Soil (HS), Hardening Small Strain (HSS), et Soft Soil (SS) est mise en avant et clarifiée dans le contexte des exigences Eurocodes 7 pour les exemples d'excavations profondes en argile dure. Les défis d'une factorisation de la résistance au cisaillement lors de l'utilisation de paramètres de contrainte effective sont également abordés, et l'effet du modelé de sol est étudié.

1 INTRODUCTION

While the Finite Element Method (FEM) has been traditionally used in geotechnical engineering to obtain deformations and check for Serviceability Limit State (SLS), there are still a number of issues that need further research before the Ultimate Limit State (ULS) design can be routinely performed with FEM. Simpson (2012) and Simpson & Junaideen (2013) give a good review of most of the challenges associated with the ULS design with FEM. In this paper, the feasible use of different soil models such as the Mohr-Coulomb (MC), the Hardening Soil (HS), the Hardening Small Strain (HSS) and the Soft Soil (SS) models for ULS design is highlighted and better understood in the context of the EC7 requirements using deep supported excavation examples in stiff clay. The challenges of deriving structural forces using numerical methods and the effect of the soil model used are addressed. The resulting discrepancies are highlighted and better understood using a Crossrail station box case study. The challenges of factoring undrained shear strength when using effective stress model parameters are also discussed while the effect of the soil model is again illustrated by the authors.

2 MATERIAL FACTORING STRATEGIES

EC7 suggests three different Design Approaches (DAs) and each National Standard Body has chosen which approach is preferable. DA1, which is adopted in the UK, has two different combinations (sets of partial factors). In general, we could say that DA1-1 and DA2 are Load Factoring Approaches (LFAs) as the factors are applied to actions or action effects while DA1-2 and DA3 are Material Factoring Approaches (MFAs) as the soil strength parameters have to be factored.

There are two different ways to factor soil strength in FEM in staged construction problems which have arisen from the lack of guidance in the code (Katsigiannis et al, 2014). In Strategy 1, the material parameters are factored from the beginning so the analysis is performed with the design values of soil strength. On the other hand, in Strategy 2, calculations are performed with characteristic values and at critical stages the material parameters are reduced to their design values. A good description of the two strategies has been given by Simpson (2012). Katsigiannis et al. (2014) have also discussed the advantages and disadvantages of the two strategies which are summarized in Table 1.

Table 1. Advantages and disadvantages of the two material factoring strategies

Strategy 1	Strategy 2
✓ It is straightforward and easy ✓ It can be applied in many situations, not only in staged construction problems	✓ More critical in terms of design structural forces ✓ It can be used in conjunction with SLS and DA1-1.
X In some cases it might yield design structural forces with inadequate margins of safety	X It requires many extra construction stages X Additional computational effort and time

3 BENCHMARK EXAMPLE

The challenges of deriving design prop forces using FEM and the effect of the soil model used are addressed for deep excavation in stiff, highly overconsolidated clay. The geometry of the problem is given in Figure 1.

3.1 Analysis Description

The computer software PLAXIS V12.01 was used for the analysis in its two-dimensional version. The analysis was repeated with different soil models assuming undrained conditions: the Mohr-Coulomb (MC), Hardening Soil (HS) and Hardening Small Strain (HSS) models. In all the analyses, typical stiff highly OC clay total stress parameters were used which are listed in Tables 2 and 3. The soil stiffness properties for HS and HSS are taken from Schweiger (2010). The following modelling sequence was analysed (an overdig of 0.5m is considered):

- Stage 0 Initial state conditions
- Stage 1 Wall installation and 10kPa surcharge
- Stage 2, 4, 6, 8, 10 and 12 Excavation of 4m of soil
- Stage 3, 5, 7, 9 and 11 Install strut

Table 2. Mohr-Coulomb parameters

Total stress parameters	
γ_{sat} (kN/m^3)	20
c_u (kPa)	60+8z
E_u (kPa)	1000c_u
Effective stress parameters	
c' (kPa)	0
φ' (°)	25
ψ (°)	0

Table 3. HS and HSS model parameters

Total stress parameters	
γ_{sat} (kN/m^3)	20
c_u (kPa)	60+8z
E_{50}^{ref} (kPa)	30000
E_{oed}^{ref} (kPa)	30000
E_{ur}^{ref} (kPa)	100000
power m	0.5
R_f	0.9
p_{ref} (kPa)	100
σ_{tens} (kPa)	15
ν'_{ur}	0.2
Effective stress parameters	
c' (kPa)	0
φ' (°)	25
ψ (°)	0
Additional Hardening Small Strain model parameters	
G_o	150000
$\gamma_{0.7}$	0.0002

Table 4. Soft Soil model parameters

Effective stress parameters	
γ_{sat} (kN/m^3)	20
c' (kPa)	0
φ' (°)	25
ψ (°)	0
λ*	0.189
κ*	0.0092
M	1.435
ν'	0.2

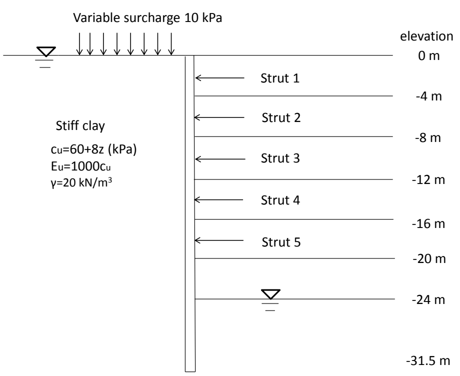

Figure 1. Geometry of deep excavation supported by 5 levels of props

3.2 *Results*

Factoring soil strength from the beginning (i.e. Strategy 1) has a very small effect on the calculated prop loads. In Strategy 2, however, the soil strength is suddenly reduced at each excavation stage. Shifting from characteristic to factored soil strengths has, as result, shown that the lowest prop receives a higher load increment than the props above (see Figure 2). At the final excavation stage the load of the lowest prop increases relative to the characteristic by 17.5%, 25.8% and 32.8% for K_0 values of 1, 1.2 and 1.5 respectively (only the K_0=1.2 case is presented here). The increase of the load of the lowest prop is due to the development of a plastic zone at the bottom of the excavation (see Figure 3). The larger the plastic zone is, the larger is the increase of the prop load when shifting from characteristic to factored strength.

Figures 4 to 6 show computed prop loads for three different soil models, increasing in sophistication. In each case, DA1-1 returns the highest prop loads. For the simplest model (elastic-Mohr Coulomb), DA1-2 Strategy 1 returns significantly lower prop loads. Use of more advanced soil models such as the HS and HSS Plaxis models can result in much smaller differences in calculated prop loads from the two material factoring strategies of DA1-2. The difference between the two DA1 combinations becomes smaller too.

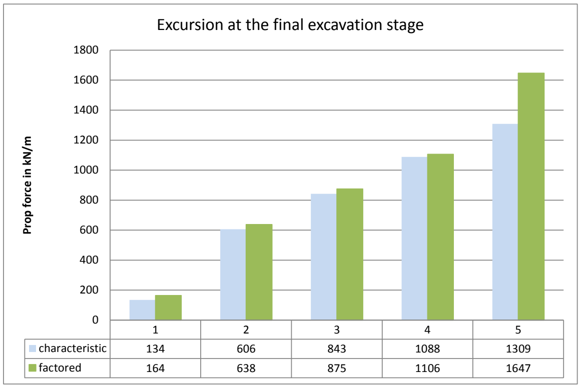

Figure 2. Prop loads before and after factoring soil strength in Strategy 2 at the final excavation stage

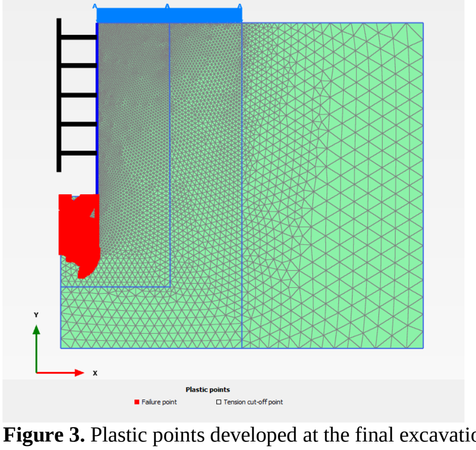

Figure 3. Plastic points developed at the final excavation stage

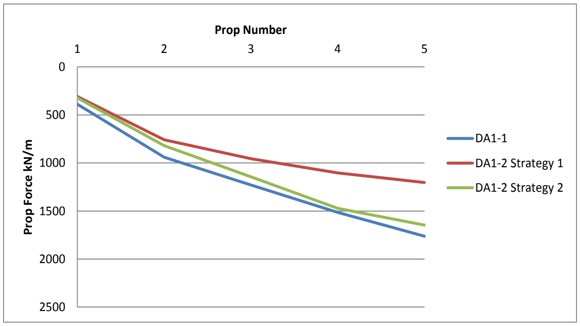

Figure 4. Maximum prop loads from different factoring strategies using MC soil model

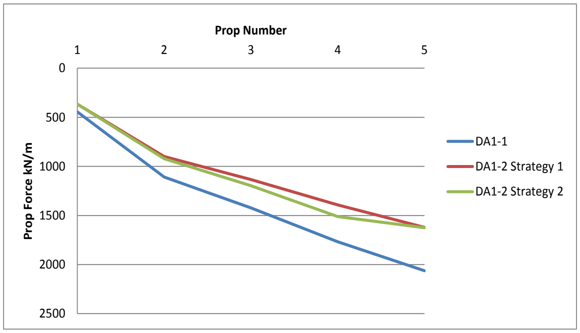

Figure 5. Maximum prop loads from different factoring strategies using HS soil model

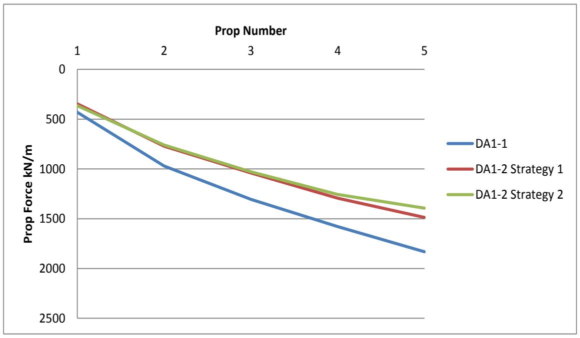

Figure 6. Maximum prop loads from different factoring strategies using HSS soil model

4 CROSSRAIL CASE STUDY

The resulting discrepancies are now highlighted using a more realistic and deeper excavation based on the Crossrail Moorgate station box case study. The geometry and construction sequence are related to the proposal made by Zdravkovic et al. (2005). However, a simplification of the geometry was undertaken in order to provide an easier understanding of the different factoring strategies.

4.1 *Analysis Description*

The computer software PLAXIS EA was used for the analysis in its 2D version. The Mohr-Coulomb (MC), Hardening Soil (HS) and Hardening Small Strain (HSS) soil models were again chosen. The finite element mesh is shown in Figure 7. The concrete wall is 1.2m thick and is supported by 7 levels of steel tube props. The total stress soil parameters given in Tables 2 and 3 were used for the FEM simulations.

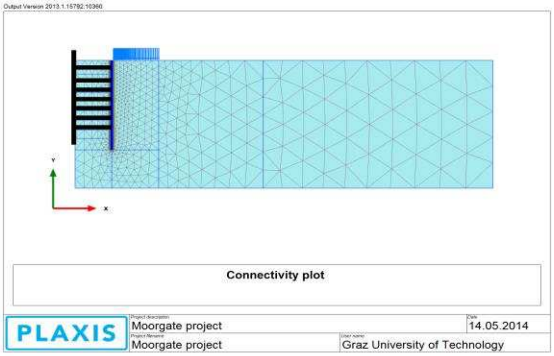

Figure 7. Finite Element mesh

4.2 *Results*

Factoring soil strength from the beginning (i.e. Strategy 1) has very little effect on calculated prop loads, which is in good agreement with findings in the benchmark example. In general it seems that soil strength is not critical for the materials and geometry considered. In Strategy 2, shifting from unfactored to factored strength has shown that the lowest prop, again, receives a higher load increment. At the final excavation stage the load of the lowest prop increases by 21.64%. DA1-1 governs the prop design in all cases while use of more advanced soil models again results in much smaller differences in calculated prop loads from the two material factoring strategies of DA1-2 (Figures 8 to 10).

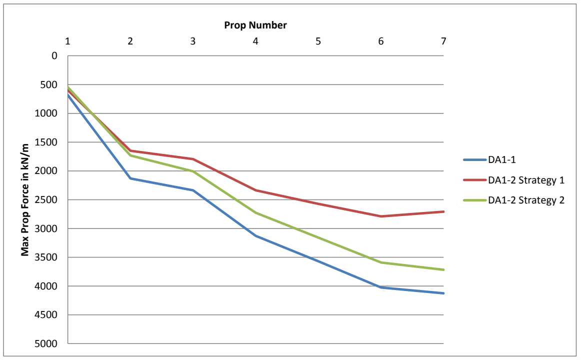

Figure 8. Maximum prop loads from different factoring strategies using MC soil model

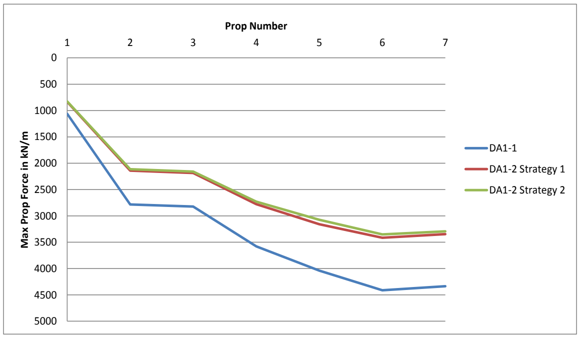

Figure 9. Maximum prop loads from different factoring strategies using HS soil model

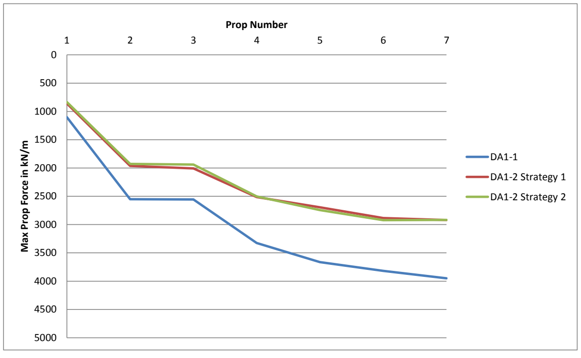

Figure 10. Maximum prop loads from different factoring strategies using HSS soil model

5 FACTORING UNDRAINED STRENGTH

How the undrained soil strength should be factored is one of the most common misunderstandings of EC7. In the analyses presented in this paper in Sections 3 and 4, total stress conditions were assumed. The undrained shear strength c_u was input, i.e. the analysis was performed in terms of total stresses, so the software user could simply apply the partial factor of 1.4 as the code requires. However, when undrained analysis is performed with effective stress parameters, c_u is not input but it is the result of the soil model used. What is usually overlooked during the design is that the designer should always check that the calculated c_u profile corresponds to the characteristic one, factored by a specified sufficient value. While there is still an ongoing debate, the authors understand that the members of EG4 (the EC7 Evolution Group working on numerical methods) have agreed on a value of 1.4.

A series of triaxial undrained compression single element tests were performed with MC, SS, HS and HSS soil parameters at different depths (0.5, 2, 5, 10, 15, 30 and 45m below ground level) following isotropic consolidation. The SS parameters are based on the ones used by Schütz (2006). A pre-consolidation pressure of 2000kPa is applied while an underdrained profile is assumed in all cases. It can be seen in Figure 11 that, for this heavily overconsolidated clay, the calculated characteristic undrained shear strength profile from MC, SS and HS triaxial undrained compression tests (in effective stresses) are identical and in close agreement with the assumed c_u profile in total stresses.

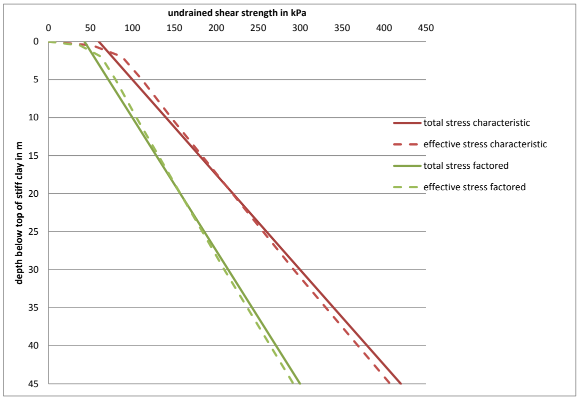

Figure 11. Characteristic and design undrained shear strength profiles using total and effective stress MC, HS and HSS parameters

Also, factoring tanφ' by 1.4 produces a set of undrained strengths equivalent to EC7 requirement where the undrained strength is factored by a partial factor γ_{cu}=1.4. The agreement is not good with HSS model as the stress path is different (see Figure 12).

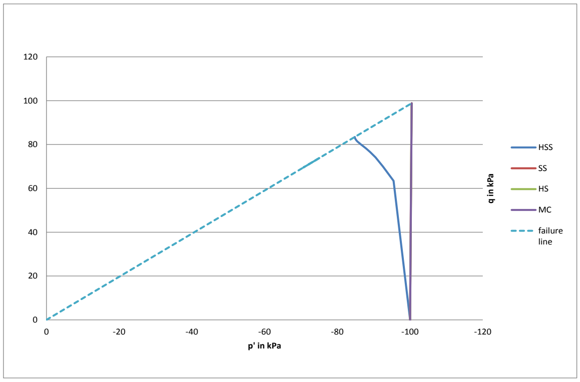

Figure 12. p-q stress paths using different soil models

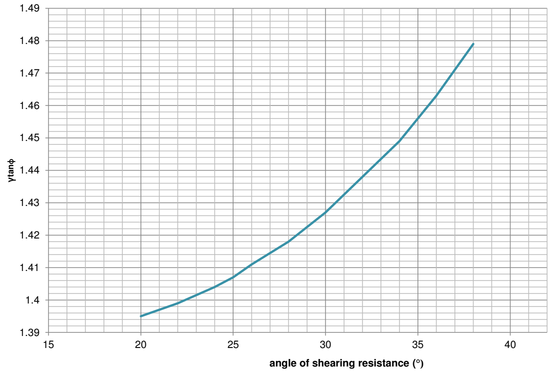

Figure 13. $\gamma_{tan\varphi'}$ for different values of angle of shearing resistance

Figure 13 gives the value of $\gamma_{tan\varphi'}$ for different values of angle of shearing resistance that results in a calculated c_u profile equal to the characteristic one, factored by 1.4. The graph enables the designer to use appropriate values of $\gamma_{tan\varphi'}$ when undrained analysis is performed with effective stress parameters. However, the graph is only correct when the triaxial stress path is vertical (in this case for the MC, HS and SS models). It is more difficult to draw general rules for non-vertical stress paths.

6 CONCLUSIONS

While a broader study is needed, some useful conclusions can be drawn from the work done in this article:

- Use of more advanced soil models such as the HS and HSS Plaxis models can result in much smaller differences in calculated prop loads from the different material factoring strategies for the geometries and materials considered in this study and for total stress analysis.
- The choice between the two DA1-2 strategies is not important in practice to DA1 so long as the design is governed by DA1-1.
- When using effective stress parameters for undrained analysis, the designer should always check that the calculated c_u profile corresponds to the characteristic one, factored by 1.4 as EC7 requires.

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