Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-1105

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Tomorrow's geotechnical toolbox: EN 1997-1:202x Numerical methods

La boîte à outils géotechnique de demain: EN1997-2:202x Méthodes numériques

A. S. Lees
Geofem Ltd., Nicosia, Cyprus; member of SC7 PT2

ABSTRACT: This paper describes a new set of rules to cover geotechnical design and the verification of limit states using numerical methods as developed for the final Project Team (PT) draft of the next generation of Eurocode 7 Part 1 (EN 1997-1:202x). If adopted, this would be the first geotechnical design code to include such a set of rules and reflects the growing use of numerical methods in geotechnical engineering. While the resistance factoring approach (RFA) may be used to verify adequate safety against a particular failure form occurring in relatively simple cases, the material factoring approach (MFA) is recommended for a more robust verification of all possible geotechnical ultimate limit states using numerical methods. The action effect factoring approach (EFA) applies a relatively constant safety margin to structural forces in most cases but there are some situations where lower than expected ground strength has a significant effect on structural forces and EFA would not provide adequate reliability. Therefore, a dual factoring approach (MFA and EFA) is recommended where the most onerous structural forces obtained from each are used in the verification of structural ULS. Some other recommendations on the use of numerical methods contained in the redrafted EN 1997-1 are also summarised in this paper.

RÉSUMÉ: Ce document décrit un ensemble de nouvel règles couvrant la conception géotechnique et la vérification des valeurs limites à l'aide de méthodes numériques, développées pour l'équipe finale de projet (PT), projet du future génération d'Eurocode 7 Partie 1 (EN 1997-1: 202x). S'il est accepté, ce code de conception géotechnique serait le premier à inclure un tel ensemble de règles et refléterait l'utilisation croissante des méthodes numériques en ingénierie géotechnique. Bien que l'approche par factorisation de la résistance (RFA) puisse être utilisée pour vérifier la sécurité adéquate contre une forme de défaillance particulière se produisant dans des cas relativement simples, l'approche par factorisation des matériaux (MFA) est recommandée pour une vérification plus robuste de tous les états limites ultimes géotechniques possibles, à l'aide de méthodes numériques . L'approche par factorisation d'action d'éffet (EFA) applique une marge de sécurité relativement constante aux forces structurelles dans la plupart des cas, mais dans certaines situations, une résistance au sol plus faible que prévu a un effet significatif sur les forces structurelles, et une EFA ne fournit pas une fiabilité suffisante. Par conséquent, une approche à double factorisation (AMF et EFA) est recommandée dans laquelle les forces structurelles les plus lourdes obtenues de chacun sont utilisées dans la vérification des ELU structurels. Le présent document résume également certaines autres recommandations sur l'utilisation des méthodes numériques contenues dans la nouvelle version de l'EN 1997-1.

Keywords: Eurocodes; finite element method; geotechnical design.

1 INTRODUCTION

The redrafting of EN 1997 Part 1 General Rules is described in one (Franzen et al, 2019) of the series of papers on the theme "Tomorrow's geotechnical toolbox" at this conference. This paper focusses on those clauses in the proposed draft by Project Team 2 (PT2) covering geotechnical design and limit state verification using advanced numerical methods such as finite element analysis (FEA). If these clauses were adopted in the final version of the code then EN 1997 will be the first geotechnical design code with a set of rules specifically intended for design using advanced numerical methods.

This fulfils one of the tasks listed by CEN/TC250 to establish "clear rules for using advanced numerical methods in day-to-day practice" which reflected the fact that the implementation of many aspects of the current EN 1997 using numerical methods were unclear, in spite of the increasing use of such tools in everyday design. It may also help to address the inconsistent application of such techniques across Europe as noted in benchmark studies (Potts et al (2002), Schweiger (2006)). This task was based on the recommendations of Evolution Group 4 (numerical methods) – one of a number of expert groups formed by TC250/SC7 to recommend improvements to Eurocode 7 in key technical areas.

The most commonly-used advanced numerical method – the displacement finite element method – is well suited to displacement prediction and hence the verification of serviceability limit states (SLS). However, FEA and other numerical methods are seeing increasing use in the verification of ultimate limit states (ULS). There are advantages to this, including the simultaneous checking of multiple failure forms which are not pre-determined, verifying serviceability and ultimate limits states (SLS and ULS) with one analysis model (using incremental methods) and more accurate simulation of ground behaviour and soil-structure interaction with the various constitutive relationships that are available. However, there are many difficulties to overcome and pitfalls to avoid for the successful verification of geotechnical ULS by numerical methods. Many of these arise from the difficulty of accurately simulating a failure state whose occurrence should be highly unrealistic. How should the model be made to fail and then how should sufficient likelihood of it not occurring be determined?

The current version of EN 1997 contains no rules specifically for advanced numerical methods except for the occasional permission or recommendation for their use in certain circumstances. This led various researchers to investigate the use of numerical methods in accordance with EN 1997. Some highlighted issues arising from the difficulties of simulating the large plastic strains associated with ground failure, e.g. influence of mesh refinement, and the effects on soil strength of stress ratio, deformation parameters and consolidation, as described by Potts & Zdravkovic (1999, 2001) and summarised in Bauduin et al (2005). Design code-specific issues, in particular the introduction of partial factors, have been studied extensively with several publications covering benchmark and case study numerical analyses performed in accordance with EN 1997 (Schweiger, 2010a,b; Schweiger et al, 2010; Simpson and Hocombe, 2010; Bauduin et al, 2003) and wider discussions of the various issues (Bauduin et al, 2000, 2005; Simpson and Yazdchi, 2003; Heibaum and Herten, 2009, 2010); Lees (2017).

2 GENERAL CLAUSES

The importance of user competency is reaffirmed in the general section on numerical methods, along with validation of analysis outputs and the use of parametric studies to help determine the reliability of outputs.

With conventional analysis methods, e.g. limit equilibrium or limit analysis, once the calculation method has been selected, taking due cognisance of its assumptions, limit state verifications are affected by a small number of parameters. Simple application of partial factors is usually sufficiently reliable for routine design by deterministic methods. However, due to the complexity of numerical methods, there are many influences on the prediction of limit states and simple reliance on partial factors could be dangerous. It is therefore a requirement to consider the sensitivity of limit state verifications to a number of aspects, including:

- discretisation of geometry, including discontinuities;
- initial stress states;
- preceding construction stages;
- boundary conditions;
- drainage conditions (including permeability);
- ground constitutive behaviour (including stiffness, dilatancy, anisotropy, yield criteria and flow rules);
- strength and stiffness of structural elements.

3 SLS VERIFICATION

A short section on SLS in the proposed draft highlights the improved predictions of deformations that can be obtained with advanced constitutive models with non-linear stiffness, for example. It also highlights the difference between SLS verification and best-estimate predictions of deformations (using estimates of mean values of material properties). A common error by some users of numerical methods is to compare the output from SLS verification analyses with site monitoring data, expecting reasonable agreement even though cautious values of ground and structure parameters, geometry, sequencing, etc and full permanent and variable loading may have been adopted in the model. Such comparisons should be made with best-estimate parameters – the definition of which has been added to the new draft.

4 ULS VERIFICATION

Given the difficulty of accurately simulating a failure state whose occurrence should be highly unrealistic, the question was asked earlier in this paper: "How should the model be made to fail and then how should sufficient likelihood of it not occurring be determined?" In brief summary, there are essentially three (two in practice) options for verifying geotechnical ULS (structural ULS is discussed later) using numerical methods:

a) Reduce ground strength until failure occurs. The ground strength values when the first (most critical) failure occurs should be less than the factored (design) values.
b) Reduce ground resistance. In practice this is the same as (a) because resistance is not a direct input parameter to the calculation. Pile, ground anchor and soil nail resistances can be set to design values in the input to a numerical model and the program will set the material strengths so that their resistances cannot be exceeded. Resistances can also be determined using numerical methods (see (c)).
c) Increase load or displacement until the intended failure mechanism occurs. The load at which failure occurs is the resistance of the intended failure form which, when factored, should be greater than or equal to the corresponding design load. This needs to be repeated for all failure forms for which a resistance needs to be calculated if this approach is adopted throughout.

4.1 Material factoring approach (MFA)

Approach (a) summarised above is MFA. Factors are applied to input parameters (material strength and some actions) such that design values of output are obtained directly. The recommended way to apply these factors is to reduce ground strength in a stepwise fashion to the design values to determine design values of structural forces and to check for any geotechnical failure. Strength reduction may be continued to identify the most critical failure form. MFA is suited to verifying ULSs involving ground failure but its effect on structural forces is rather unpredictable, so it is less suited to verifying ULS of structural elements alone.

4.2 Action effect factoring approach (EFA)

Action effects are the output from calculations, such as pile axial load or wall bending moment. Except for a small factor on variable actions, input parameters remain at their characteristic values so EFA has the advantage of allowing the numerical analysis to be performed with more representative input parameters. Outputs are factored and then compared with factored resistances to verify ULS. It is suited to the verification of structural ULS but may provide insufficient reliability in cases where lower than expected ground strength has a significant effect on structural forces, e.g. forces in stabilisation measures to a marginally stable slope. In such cases, MFA provides more reliable design values of structural forces.

4.3 Resistance factoring approach (RFA)

Whether resistances are determined by numerical methods, measurement or other calculation method, design values of action effects from EFA are compared with their corresponding design values of resistance. The drawbacks of RFA (Lees, 2017) mean that it is suited only to the verification of ULS axial resistance of piles, nails, ground anchors and similar structures, and to the verification of certain failure forms in simple, externally loaded geotechnical structures. MFA is recommended in the new draft of EN 1997-1 for the general verification of geotechnical ULS.

4.4 Obtaining design structural forces

Outputs of structural forces (e.g. wall bending moment, strut axial force, pile axial load) are required in order to verify adequate resistance in structural elements in accordance with the relevant Eurocode. Adequate reliability is ensured in most cases by factoring output by EFA using the factor on permanent unfavourable actions. Variable actions are factored at source in the input by the ratio of the partial factors for variable and permanent actions. EFA has the advantage of allowing numerical models to be run with more realistic, largely unfactored actions and applying a relatively constant level of conservatism to structural forces. Factoring all actions at source can have an inconsistent effect on structural forces if the higher load causes yielding in the ground because both higher and lower output can be obtained (Lees, 2013).

MFA is not suited on its own to obtaining sufficiently reliable design values of structural forces because in non-yielding soil a partial factor on ground strength can have no effect on structural force outputs, while increased yield can have inconsistent effects since both higher and lower structural forces may be obtained depending on the specific case. However, there are cases where weaker than expected ground can have a significant effect on structural forces and which would be missed by EFA alone. For example, structural support such as a retaining wall provided to a marginally stable slope would typically show low or zero values of structural forces with ground strength factored by 1 because the slope is stable. However, to ensure that the retaining wall had adequate resistance if ground strength were lower and the wall needed to support the slope, design structural forces using MFA also need to be obtained.

4.5 Dual factoring approach

Since no single factoring approach is sufficiently robust to verify ULS by numerical methods across a range of geotechnical structure types, a dual factoring approach to the determination of design values of structural forces is recommended in the new draft of EN 1997-1, with ground failure verified by MFA, as described in Figure 1. In many cases, design values of structural forces obtained by EFA will be the most onerous and these will be used to verify structural ULS. However, in some cases, design values obtained by MFA will be more onerous (e.g. in marginally stable slopes) and these should be used to verify structural ULS, hence the dual (EFA and MFA) approach. The same applies for design values of axial force in piles, soil nails, ground anchors and rock bolts, the most onerous of which would be compared with design values of axial resistance for these structures.

4.6 Applying partial factors to input parameters

The first stage of many simulations using numerical methods in geotechnical engineering involves establishing in situ stresses. Were these to be established with factored ground strength could lead to unrealistic stresses that influence outputs. Similarly, factoring ground strength and actions throughout multiple, consecutive construction stages may have hard to predict consequences on subsequent construction stages with higher or lower degrees of conservatism than intended.

Consequently, rather than apply factors at the start of an analysis, it is recommended in the new draft of EN 1997-1 to run analyses with characteristic values throughout the construction sequence and to reduce ground strength, apply factors to actions and adopt design water regimes in separate adjunct stages at critical phases in the construction sequence.

The strength reduction may be performed simply by substituting the material model parameters for those with a lower, factored strength or by means of a stepwise strength reduction procedure, if available (Potts and Zdravković, 2012; Tschuchnigg et al, 2015).

Once the design value of ground strength is reached, ULS in the ground is verified by obtaining equilibrium in the calculation and interpreting from displacement output that a failure mechanism was not obtained. Design values of structural forces from MFA are also obtained. Strength reduction may be continued beyond this point to determine the most critical geotechnical failure.

It is permitted to combine ground strength reduction with structural strength or resistance reduction to help identify potentially critical collapse mechanisms of combined ground and structure failures. But a warning is given that this may result in less conservative structural forces being obtained.

5 NUMERICAL METHODS IN EN 1990

The current proposed draft of EN 1990 contains a subclause about non-linear analysis in the clause "Structural analysis and design assisted by testing" which addresses mainly numerical methods. The recommendations there deal with the necessity of validation of the models against benchmarks, of basic tests on materials, of physical reference tests and mesh sensitivity tests. Further it is stated that key parameters should be entered into the limit state function as characteristic values and other parameters should be entered as mean values. A sensitivity study should be carried out – in case of non-linearity between the resistance and the variables influencing the resistance – to determine the most sensitive input parameter and how to apply the partial factors given in the Eurocodes.

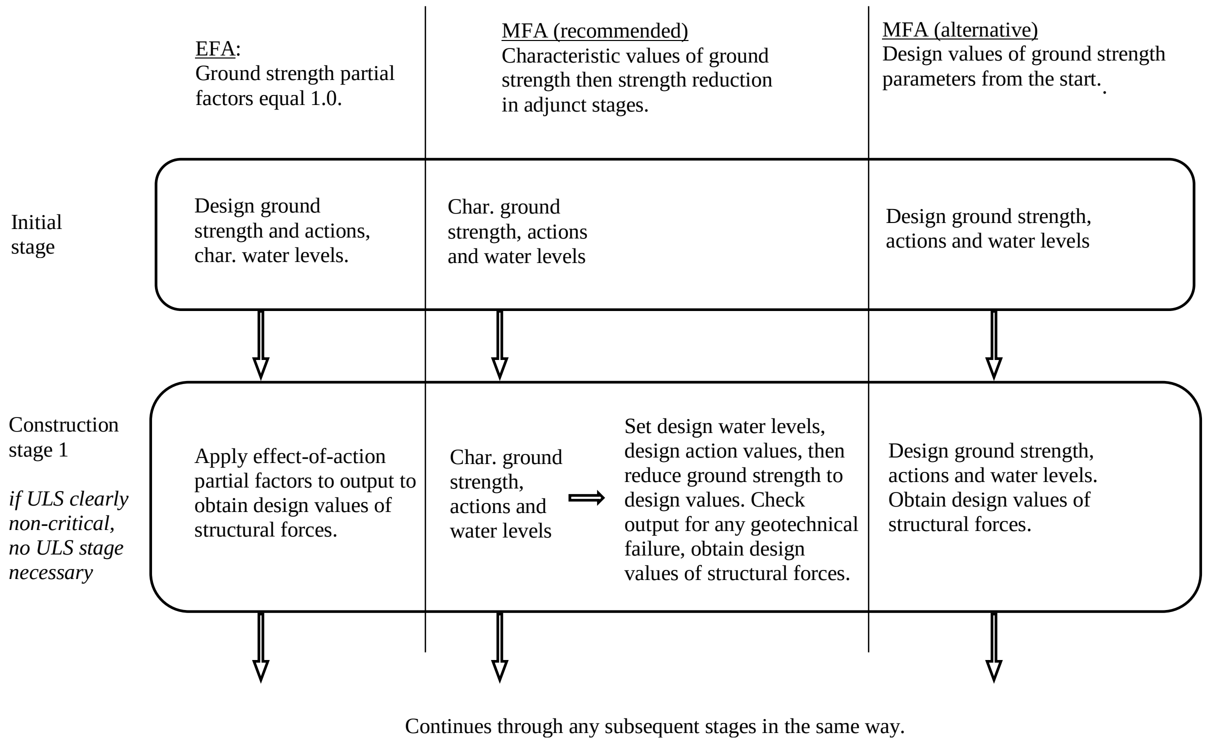

Figure 1 Recommended factoring procedure in new draft of EN 1997-1.

6 CONCLUSIONS

The proposed draft of EN 1997-1 Geotechnical design - General Rules contains a new set of rules for the verification of limit states using advanced numerical methods. These have been summarised and justified in this paper. For ULS verifications two combinations of partial safety factors should be applied to help ensure sufficient reliability against ultimate limit states occurring in the ground and structural elements for different types of geotechnical constructions.

7 REFERENCES

Bauduin, C., De Vos, M., Simpson, B. 2000. Some considerations on the use of finite element methods in ultimate limit state design, *LSD2000: Proc. Int. Workshop on Limit State Design in Geotechnical Engineering*, Melbourne, Australia, 18th Nov.

Bauduin, C., De Vos, M., Frank, R. 2003. ULS and SLS design of embedded walls according to Eurocode 7, *Proc. XIII ECSMGE*, Prague, Czech Republic; Vol. 2: 41-46.

Bauduin, C., Bakker, K.J., Frank, R. 2005. Use of finite element methods in geotechnical ultimate limit state design, *Proc. XVI ICSMGE*, Osaka, 2775-2779.

Heibaum, M., Herten, M. 2009. Geotechnical verifications using the finite-element method?, *Bautechnik*, Special Issue, DOI: 10.1002/batc.200910037, 7-15.

Heibaum, M., Herten, M. 2010. Verifications in accordance with EC7 / DIN1054 using numerical methods, *14th Danube-European Conf. on Geotechnical Engineering*, 2-4th June, Bratislava, Slovakia.

Lees, A.S. 2013. Using numerical analysis with geotechnical design codes, in *Modern Geotechnical Design Codes of Practice* (eds. Arnold, Fenton, Hicks, Schweckendiek and Simpson). IOS Press, Amsterdam, pp. 157-170.

Lees, A.S. 2017. The use of geotechnical numerical methods with Eurocode 7, *Proceedings of the ICE Engineering Analysis and Computational Mechanics* **170(4)**, 146-153.

Potts, D.M., Zdravkovic, L. 1999. *Finite Element Analysis in Geotechnical Engineering: Theory*, Thomas Telford, London.

Potts, D.M., Zdravkovic, L. 2001. *Finite Element Analysis in Geotechnical Engineering: Application*, Thomas Telford, London.

Potts, D.M., Zdravkovic, L. 2012. Accounting for partial material factors in numerical analysis, *Géotechnique* **62(12)**, 1053-1065.

Potts, D., Axelsson, K., Grande, L., Schweiger, H., Long, M. 2002. *Guidelines for the use of advanced numerical analysis*, Thomas Telford, London.

Schweiger, H.F. 2006. Results from the ERTC7 benchmark exercise, *Numerical Methods in Geotechnical Engineering* (ed. Schweiger), 3-8.

Schweiger, H.F. 2010a. Design of deep excavations with FEM – influence of constitutive model and comparison of EC7 design approaches, *Proc. of the 2010 Earth Retention Conference*, Aug. 1-4, 2010, Bellevue, WA, USA, 804-817.

Schweiger, H.F. 2010b. Numerical analysis of deep excavations and tunnels in accordance with EC7 design approaches, *Int. Conf. Geotechnical Challenges in Megacities*, Moscow, 7-10th June, 206 – 217.

Schweiger, H., Marcher, T., Nasekhian, A. 2010. Nonlinear FE analysis of tunnel excavation – comparison of EC7 design approaches, *Geomechanics and Tunnelling* **3(1)**, 61-67.

Simpson, B., Hocombe, T. 2010. Implications of modern design codes for earth retaining structures, *Proc. of the 2010 Earth Retention Conference*, Aug. 1-4, 2010, Bellevue, WA, USA, 786-803.

Simpson, B., Yazdchi, M. 2003. Use of finite element methods in geotechnical limit state design, *LSD2003: Int. Workshop on Limit State Design in Geotechnical Engineering Practice*, Cambridge, MA, USA, 26th June.

Tschuchnigg, F., Schweiger, H.F., Sloan, S.W., Lyamin, A.V., Raissakis, I. 2015. Comparison of finite-element limit analysis and strength reduction techniques, *Géotechnique* **65(4)**, 249-257.