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EUROCODE 7 AND DESIGN OF DEEP EXCAVATIONS AND TUNNELS USING FINITE ELEMENT METHOD

Abstract

Advanced numerical methods, such as the finite element method (FEM), are widely used in geotechnical engineering practice to predict displacements induced by deep excavations and tunnel construction. While the finite element method is primarily used to obtain displacements and hence to verify serviceability limit states (SLS), it is also increasingly used for geotechnical ultimate limit state (ULS) design. The introduction of the Eurocode 7 and the associated concept of partial safety factors has replaced the global safety factor concept which had previously been used in geotechnical design practice. Eurocode 7 introduces partial safety factors on actions (loads), materials and resistances. Three design approaches (DA1, DA2 and DA3) that differ in the combination of partial factors are available in the current version of Eurocode 7, however, the guidance as to how the partial factors should be applied in numerical analysis is not provided. The second generation of Eurocode 7 is currently being prepared, and the proposed draft of Eurocode 7 Part 1 (EN 1997-1:202x) contains a new set of rules covering geotechnical design and the verification of limit states using advanced numerical methods. In order to ensure sufficient reliability in relation to the ultimate limit states occurring in the ground and structural elements, two combinations of partial safety factors have to be applied, i.e. ULS verification with numerical models has to be performed by reducing the ground strength parameters and by increasing the structural forces in accordance with applied design approach. Although Eurocode 7 has no specific parts devoted to the design of tunnels, it is increasingly used in practice, at least for shallow tunnels in soil, since there are no European standards for tunnel design.This paper gives an overview of the procedures for applying finite element method and design approaches defined in Eurocode 7 to design of deep excavations and tunnels.

Keywords

Eurocode 7, tunnels, deep excavations, finite element method

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1. INTRODUCTION

Advanced numerical methods, such as the finite element method (FEM), are widely used in geotechnical engineering practice to predict displacements induced by deep excavations and tunnelling, especially when settlements above shallow tunnels in soft ground have to be assessed. While the finite element method is primarily used to obtain displacements and hence to verify serviceability limit states (SLS), it is also increasingly used for geotechnical ultimate limit state (ULS) design.

Eurocode 7 (EN 1997) is the primary geotechnical design code in Europe. The introduction of the Eurocode 7 and the associated concept of partial safety factors has replaced the global safety factor concept which had previously been used in geotechnical design practice. Eurocode 7 introduces partial safety factors on actions (loads), materials and resistances. Three design approaches (DA1, DA2 and DA3) are available in Eurocode 7 and different countries have adopted different design approaches in their national annexes. However, the current version of Eurocode 7 does not provide guidance as to how the partial safety factors should be applied in numerical analysis. This paper gives an overview of the procedures for applying finite element method and design approaches defined in Eurocode 7 to design of deep excavations and tunnels. Although Eurocode 7 has no specific parts devoted to the design of tunnels, it is increasingly used in practice, at least for shallow tunnels in soil, given that currently there are no European standards for tunnel design.

2. OVERVIEW OF EUROCODE 7

Eurocode 7: Geotechnical design [1] requires that for each geotechnical design situation it is verified that no relevant limit state has been exceeded. Limit states (failure) can occur either in the ground or in the structure or by combined failure of the ground and the structural elements. Allowed procedures for verification of limit states are: calculations, adoption of prescriptive measures, experimental models and load tests, as well as the observational method. Both short-term and long-term design situations must be considered. Geotechnical design by calculation can be performed using analytical, semi-empirical or numerical model. When the interaction between the structure and the soil at a limit state are considered it is appropriate to use numerical methods. Verification of ultimate limit states (ULS) and serviceability limit states (SLS) are required.

Geotechnical design by calculation are based on actions (imposed loads or imposed displacements), material properties (soils, rocks and other materials) and geometrical data, as well as on calculation models and limiting values of deformations (crack widths, vibrations etc.). Uncertainties are taken into account by applying partial safety factors. When considering a limit state of rupture or excessive deformation of a structural element or section of the ground (STR and GEO), it must be verified that the design effects of actions E_d do not exceed the design resistances R_d. Partial factors may be applied either to the actions (F_{rep}) or to their effects (E), as well as to the ground properties (X) or resistances (R) or both. When the partial factors are applied to the characteristic (representative) values of the selected parameters, the design values are obtained. The characteristic value of a geotechnical parameter has to be selected as a cautious estimate of the value affecting the occurrence of the limit state. In Eurocode 7, there are three Design Approaches (DA) that differ in the combination of sets of partial factors. Table 1 shows the partial factors for the given design approaches (two separate analyses are required for design approach 1). It has to be noted that different countries have adopted different design approaches in their national annexes. Values of partial factors for serviceability limit states should be taken equal to 1.0.

Table 1. Eurocode 7 design approaches and partial factors

				DA1/1	DA1/2	DA2	DA3
Partial factors on actions (γ_F) or the effects of actions (γ_E)	Permanent	Unfavourable	γ_G	1.35	1.0	1.35	1.0
		Favourable		1.0	1.0	1.0	1.0
	Variable	Unfavourable	γ_Q	1.5	1.3	1.5	1.3
		Favourable		0	0	0	0
Partial factors for soil parameters (γ_M)	Angle of shearing resistance		$\gamma_{\varphi'}$	1.0	1.25	1.0	1.25
	Effective cohesion		$\gamma_{c'}$	1.0	1.25	1.0	1.25
	Undrained shear strength		γ_{cu}	1.0	1.4	1.0	1.4
	Unconfined strength		γ_{qu}	1.0	1.4	1.0	1.4
	Weight density		γ_γ	1.0	1.0	1.0	1.0
Partial resistance factors (γ_R)	Bearing		γ_{Rv}	1.0	1.0	1.4	1.0
	Sliding		γ_{Rh}	1.0	1.0	1.1	1.0

When prediction of geotechnical behaviour is difficult, as is often the case with tunnels, Eurocode 7 allows the application of the observational method, which implies that the design is reviewed during construction. Before construction is started it is necessary to define acceptable limits of behaviour, a monitoring plan and a plan of contingency actions which may be adopted if the monitoring reveals behaviour outside acceptable limits. During construction, the monitoring has to be carried out and the results of the monitoring have to be assessed at a sufficiently early stage to allow the planned contingency actions to be undertaken successfully when the limits of behaviour are exceeded. This method, in geotechnical practice, has a much more important role in the construction of deep tunnels and rock tunnels than in construction of shallow tunnels in soft ground. In soft ground tunnelling, there is a lot of uncertainty about the amount of time available to respond to instability, so it is generally considered good practice to fully design the support measures before construction begins and to adopt only minor changes during construction.

3. THE APPLICATION OF FINITE ELEMENT METHOD

Advanced numerical methods are required for modelling complex soil-structure interaction problems. The finite element method (FEM) is a flexible tool that has been adopted by many authors. The FEM enables development of a calculation model that can be used to perform the stress-strain analysis taking into account relevant geotechnical properties of soil, complex problem geometry, initial conditions and construction stages. Before the calculation is started, it is necessary to create model geometry and boundary conditions, define material properties and generate finite element mesh. The initial step of a finite element analysis is to establish initial in-situ stress states in the ground. After that, the calculation is performed in calculation phases defined in accordance with the modelled construction stages.

In geotechnical practice, 2D numerical models are often used. However, a full 3D FE analysis is needed to adequately simulate the process of tunnel construction, i.e. the progress of tunnelling work and stress changes and deformations taking place at the temporary working face. The 3D process of tunnel construction is usually simulated using a step by step approach, especially for open-face tunnels constructed using the New Austrian Tunnelling Method (NATM) or open-face shield [2-8]. The initial step of numerical analysis is to establish the in-situ stress state in soil. The process of tunnel construction is modelled by successive removal of elements in front of the tunnel face, to simulate an unsupported excavation sequence, while successively installing lining elements to support the previous excavation. The simulation of tunnelling work has to be made on the tunnel length that is sufficient to obtain a steady state conditions behind the tunnel face. When closed-face shield tunnelling is simulated, the modelling can include some construction details such as the support pressure at the tunnel face, grouting pressure, etc. The 3D FE modelling allows the 3D effect of tunnel construction, i.e. partial stress relaxation at the tunnel face, to be modelled explicitly. However, since 3D FE modelling of tunnel construction is computationally very demanding, 2D FE models are still commonly used in routine geotechnical design. When the process of tunnel construction is modelled in plane strain, at least one assumption must be made in order to account for the 3D effects, i.e. the stress relief and ground movements occurring at the tunnel face prior to lining installation. Various methods that take into account 3D effect of tunnelling within simplified 2D plane strain analysis have so far been proposed in literature (review of methods can be found in [9]). The most commonly used method for 2D modelling of open-face tunnel construction is the stress (load) reduction method, which is actually a FE utilisation of the convergence-confinement method [10]. Partial stress relaxation occurring at the tunnel face is taken into account in the 2D model via the parameter λ which represents the percentage of unloading of the initial stresses before lining is installed. Starting from the initial geostatic stress state, the soil elements within the tunnel boundary are removed and partial stress relaxation is allowed, and in the next step the lining is installed on deformed tunnel contour (lining takes on the load $(1-\lambda)\sigma_0$, where σ_0 is the initial stress in the ground). The tunnel profile can be excavated in stages (top heading, bench and invert). The stress reduction factor λ is the controlling parameter that has to be prescribed. The parameter λ depends on a number of factors such as ground properties, tunnel geometry, construction method and round length. It can be calibrated based on a comparison of 2D and 3D FE analysis results. In practice, the parameter λ is often estimated based on engineering experience with similar tunnelling conditions or monitoring data. It should be noted that numerical models are usually calibrated based on available measurements of ground settlement, but are also used to predict tunnel lining stresses and deformations. However, it does not necessarily follow that because the ground deformations are correctly predicted the lining stresses and deformations will also be correct and one answer to this problem is to make more measurements of stresses in and on SCL tunnel linings [11].

While FEM is primarily used to predict displacements, and hence to verify serviceability limit states (SLS), it is also increasingly used for geotechnical ultimate limit state (ULS) design. The application of FEM to geotechnical design allows simulation of real ground behaviour and soil-structure interaction, the verification of serviceability and ultimate limits states using the same numerical model and the assessment of failure modes (which are not predetermined) and ground movements. However, prerequisites for the reliability of the results are appropriate extent of ground investigations, validation of calculation models and designer qualifications and experience. Parametric studies may be performed to investigate the sensitivity of limit state verifications to a calculation model inputs such as: model geometry discretization, boundary conditions, initial stress states, drainage conditions, ground properties and structural elements properties, construction stages etc.

4. THE VERIFICATION OF LIMIT STATES USING NUMERICAL METHODS

The current version of Eurocode 7 contains no rules regarding the verification of limit states using numerical methods. When applying numerical methods to verify ultimate limit states, the basic question is how to apply partial safety factors. Various researchers have investigated the applicability of Eurocodes in design using numerical methods [12-18].

When considering limit states of rupture or excessive deformation of a structural element or section of the ground (STR and GEO), the partial factors can be applied to material properties and some actions (Material factoring approach MFA), as in Eurocode 7 design approaches DA3 and DA1/2, or to the actions or the action effects and on the resistances (Load and resistance factoring approach LRFA), as in Eurocode 7 design approaches DA2 and DA1/1 [13]. The application of partial factors to soil strength parameters (MFA) in combination with numerical methods is relatively simple and enables verification of ultimate limit state in the ground and calculation of design values of action effects (structural forces). A greater challenge is the application of partial factors to actions or actions and resistances (LRFA) in combination with numerical methods. In case of tunnels, as well as retaining structures, actions and resistances derive from the same source, namely the ground. In numerical analysis, permanent actions (soil pressures) are not input data but the result of analysis. Eurocode 7, however, allows the partial factors to be applied to action effects, such as structural forces (forces and bending moments) instead of actions, and this is often referred to as the DA2* design approach. The design approach DA2* (action effect factoring approach) enables relatively simple application of numerical methods because the analysis is performed with characteristic values of geotechnical parameters and actions (except for a small factor on variable actions), and at the end of the analysis the internal forces in the structure, obtained by calculation, are multiplied by the relevant partial factor. This procedure can be applied in the case of linear behaviour of structural elements (difficulty arises when the structural elements, such as shotcrete, exhibit highly nonlinear behaviour). The application of this approach enables the assessment of the internal stability of the structure.

The application of partial factors to material parameters (MFA) can be carried out in FE ULS calculations through two different procedures [12]. The first procedure is to apply the design values of soil strength parameters from the beginning of numerical analysis through all phases of the calculation to check that no failure has occurred. The obtained values of action effects in structural elements (forces and bending moments) are design values. The second procedure implies that all phases of the calculation are performed first with the characteristic values of soil strength parameters, allowing the real stress-strain state and soil-structure interaction to be modelled. For each construction stage that requires the ultimate limit state (ULS) check, the values of soil strength parameters are gradually reduced from the characteristic to the design values, in separate calculation steps. Thus, for each construction stage, it is checked that there is no failure in the ground when the strength parameters reach the design value. The obtained values of the action effects in structural elements (bending moments and forces) are design values. The application of the second procedure is recommended, especially when the construction sequences and load history affect the calculation results and when the soil-structure interaction plays a significant role [13]. The strength reduction can be continued after the design values have been reached in order to identify the most critical failure form. The procedure for the application of partial factors to the action effects implies that all phases of the calculation are carried out with characteristic values of soil strength parameters and actions, except that the variable unfavourable load (which is externally applied action) is multiplied by the modified factor $\gamma = \gamma_G / \gamma_Q = 1.5 / 1.35 = 1.11$ (for this load the individual contribution to the action effects cannot be directly quantified). At the end of the calculation, the obtained values of action effects in structural elements (internal forces and bending moments) are multiplied by the factor $\gamma_G = 1.35$ [17, 19].

The presented procedures imply that each construction stage is simulated first using characteristic values of the actions and ground strength properties. The verification of the ultimate limit state for a certain construction stage is performed starting from the previously obtained characteristic stresses and deformations for that stage. After checking the limit state, the calculations start again from the characteristic stress and strain field and the next construction stage is simulated [13]. The ULS calculations can be performed by reducing the ground strength parameters or increasing the structural forces in accordance with applied design approach. If the ULS calculation is successfully completed (without failure), it can be concluded that the design is in accordance with the design regulations.

In geotechnical practice, the design of the supported excavation with numerical models is usually performed using the approach DA2*. This approach is typically used for the design of embedded retaining walls. However, for a retaining wall provided to a marginally stable slope, in order to ensure the adequate resistance of retaining wall, the design structural forces using MFA also need to be obtained given that the lower than expected values of ground strength may lead to the need for the wall to support the slope [19]. When applying 2D FE model to simulate tunnel construction, the ground deformations and lining stresses are controlled by prescribed stress reduction (relaxation) factor and soil strength reduction (MFA) has no significant effect. According to the Austrian directive RVS 09.01.42 (Tunnel structures in soft soil below built-up areas), the design approach DA2* should be applied for 2D FE analyses of tunnel construction. It should be noted that 3D simulation of tunnel construction enables the stress relaxation at tunnel face to be modelled explicitly. The application of material factoring approach (MFA) is appropriate for the verification of the face stability (GEO limit state). However, both GEO and STR limit states are relevant for the support design. Jones [11] investigated the effect of soil strength reduction in a 3D model of a tunnel (with sprayed concrete lining) and concluded that this approach should be applied in addition to the approach with increased values of structural forces to verify the ultimate limit state in tunnel lining (the worst case ULS lining forces).

Schweiger [14] investigated the influence of the choice of the constitutive model and the design approach on the results of finite element analyses of deep excavations and tunnels. In the 2D FE analysis of shallow NATM tunnel construction, the stress relaxation factors were applied (based on experience from projects under similar conditions) in order to account for 3D effects in an approximate manner. It was concluded that, in principle, all design approaches can be used in combination with numerical modelling, provided that DA2 is used in the form of DA2*, i.e. that partial factors are applied to the effects of action. Brinkgreve and Post [17] presented a Design Approaches facility for an efficient use of partial safety factors in a finite element environment (implemented in the FE program PLAXIS). An example was elaborated involving the geotechnical design of a sheet-pile wall supported excavation using both design approaches DA2* and DA3. Paternesi et al. [18] investigated the applicability of Eurocodes in combination with numerical analyses and presented the results of the 2D FE analysis of shallow NATM tunnel in soil. The phased excavation of tunnel profile was modelled and the 3D effects of tunnel face advancement were simulated using a pre-relaxation factor (stress reduction) for each excavation section. They concluded that the most suitable design strategy when designing shallow tunnels is to apply both DA2* and DA3 approaches (equivalent to the DA1 approach) in order to ensure a safe design from both the geotechnical and structural point of view. Also, they considered the application of a nonlinear constitutive model for shotcrete primary lining, since the application of a linearly elastic model can lead to uneconomic design. The structural safety was assessed using the M-N interaction diagrams. They concluded that a nonlinear shotcrete model can be applied in combination with design approach DA2*. Also, according to the authors, the design approach DA3 in combination with the direct application (in numerical calculation) of the partial factor on the shotcrete strength (instead of performing the final M-N check) would be in accordance with the material factoring approach, as defined in Eurocode 7 for soils.

The next generation of Eurocode 7 is currently being prepared, and the proposed draft of Eurocode 7 Part 1 (EN 1997-1:202x) contains a new set of rules covering geotechnical design and the verification of limit states using advanced numerical methods [19]. The material factoring approach (MFA) is recommended for the verification of geotechnical ultimate limit states using numerical methods. The action effect factoring approach (EFA) should be used for the verification of structural ultimate limit states but there are cases where lower than expected ground strength has a significant effect on structural forces and application of EFA alone would not ensure the adequate reliability (e.g. structural support such as a retaining wall provided to a marginally stable slope). Therefore, it is recommended that the verification of ultimate limit states by numerical models be based on the less favorable outcomes given by the MFA and EFA. The recommended procedure for ultimate state verifications is to model, as a first step, each construction stage using characteristic (representative) values of actions, ground strength parameters and groundwater level, where output values of movements and structural forces can be used for SLS verifications. As a second step, ULS verification is conducted (for critical construction stages) using MFA and EFA (alternative MFA approach is to use design values of ground strength from the start of a numerical analysis). It is allowed to combine ground strength reduction with structural strength or resistance reduction to help identify potentially critical collapse mechanisms of combined ground and structure failures (this may cause the structural forces to be underestimated).

5. CONCLUDING REMARKS

The stability of the supported excavation is primarily a problem of soil-structure interaction. To model complex soil-structure interaction problems, advanced numerical methods are required. The current version of Eurocode 7 contains no rules covering geotechnical design and verification of limit states using advanced numerical methods. Also, Eurocode 7 does not have parts explicitly dedicated to tunnel design, however, in the absence of appropriate standards, it is increasingly used in practice, especially for the design of shallow tunnels in soft ground. The second generation of Eurocodes is currently being prepared. The proposed draft of Eurocode 7 Part 1 (EN 1997-1:202x) presents the procedure for verification of ultimate limit states with numerical models. In order to ensure sufficient reliability in relation to the ultimate limit states occurring in the ground and structural elements, two combinations of partial safety factors have to be applied, i.e. ULS verification with numerical models has to be performed by reducing the ground strength parameters and by increasing the structural forces in accordance with applied design approach. The numerical analysis of all construction stages should be conducted using characteristic (representative) values of actions and soil strength parameters, and verification of ultimate limit states for critical construction stages should be carried out in separate additional calculation steps.

There are no European standards for tunnel design and the second generation of Eurocodes also does not include explicitly tunnel design. However, standardization of design and consistency in the application of partial factors in tunnel analysis are of great importance and further development of standards for tunnel design is necessary. The new standards or guidelines for the design of tunnels should be developed in accordance with the Eurocodes, taking into account the development of the second generation of Eurocodes [20].

LITERATURE

[1] *EN 1997-1. Geotechnical design: Part 1: General rules,* CEN Comité Européen de Normalization, Brussels.

[2] Swoboda G., Mertz W., Schmid A.: *"Three-dimensional numerical models to simulate tunnel excavation"*, Proc. 3rd Int. Conf. on Numerical Models in Geomechanics, Niagara Falls, 1989, 536-548

[3] Vermeer P.A., Bonnier P.G., Möller S.C.: *"On a smart use of 3D-FEM in tunnelling"*, Proc.of the 8th Int. Symp. on Numerical Models in Geomechanics – NUMOG VIII, Rome, 2002, 361–366.

[4] Ng C.W.W. and Lee G.T.K.: *"Three-dimensional ground settlements and stress-transfer mechanisms due to open-face tunnelling"*, Canadian Geotechnical Journal, 42, 2005, 1015-1029.

[5] Franzius J.N., Potts D.M., Burland J.B.: *"The influence of soil anisotropy and K0 on ground surface movements resulting from tunnel excavation"*, Géotechnique, 55(3), 2005, 189-199.

[6] Yazdchi M., Macklin S.R., Yeow H.C.: *"3D modelling of sprayed-concrete-lined tunnels in clay"*, Proc. of the Institution of Civil Engineers, Geotechnical Engineering, 159, Issue GE4, 2006, 243–250.

[7] Mašin D.: "3D *Modeling of an NATM Tunnel in High K0 Clay Using Two Different Constitutive Models"*, Journal of Geotechnical & Geoenvironmental Engineering © ASCE, September 2009, 2009, 1325-1335.

[8] Maraš-Dragojević S.: *"Analysis of ground settlement caused by tunnel construction"*, GRAĐEVINAR, 64 (7), 2012, 573-581.

[9] Potts D.M., Zdravković L.: *"Finite element analysis in geotechnical engineering: Application"*, Thomas Telford, London, 2001, 427p.

[10] Panet M., Guenot A.: *"Analysis of convergence behind the face of a tunnel"*. Tunnelling 82, The Institution of Mining and Metallurgy, London, 1982, 197-204.

[11] Jones B.D.: *"Design of SCL tunnels in soft ground using Eurocodes"*, ECCOMAS Thematic Conference on Computational Methods in Tunnelling (EURO: TUN 2007), Vienna, Austria, 2007.

[12] Bauduin C., Simpson B., De Vos M.: *"Some considerations on the use of Finite Element Methods in Ultimate Limit State Design"*, Int Workshop on Limit State Design, LSD 2000, Melbourne, 2000.

[13] Bauduin C., Bakker K.J., Frank R.: *"Use of Finite Element Methods in Geotechnical Ultimate Limit State Design"*, In: Proc XVI ICSMGE, Osaka, 2005, 2775–2779.

[14] Schweiger H.F.: *"Numerical analysis of deep excavations and tunnels in accordance with EC7 design approaches"*, Proc. Int. Conference Geotechnical Challenges in Megacities (Moskau), Vol.1, 2010, 206–217.

[15] Schweiger H.F., Marcher T., Nasekhian A.: *"Nonlinear FE-analysis of tunnel excavation – comparison of EC7 design approaches"*, Geomechanics and Tunnelling 3 (2010), No.1, 2010, 61–67.

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

[17] Brinkgreve R.B.J., Post M.: *"Geotechnical Ultimate Limit State Design Using Finite Elements"*, Proc. Geotechnical Safety and Risk V, IOS Press, 2015, 464-469.

[18] Paternesi A., Schweiger H.F., Ruggeri P., Fruzzetti V.M.E., Scarpelli G.: *"Comparisons of Eurocodes design approaches for numerical analysis of shallow tunnels"*, Tunnelling and Underground Space Technology 62, 2017, 115–125.

[19] Lees A.S.: "Tomorrow's geotechnical toolbox: EN 1997-1:202x Numerical methods", Proc. of the XVII ECSMGE-2019 Geotechnical Engineering foundation of the future, 2019.

[20] Athanasopoulo A. et al. *"Standardisation needs for the design of underground structures"*. European Commission - JRC Technical Reports. 2019.