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Assessment of the verification concepts in the next generation of Eurocode 7 for excavation retaining walls in sand using the FEM

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ABSTRACT: For numerical calculations in conjunction with ULS verifications, the draft of the new edition of EN 1997 (Eurocode 7) distinguishes between the Material Factor Approach (MFA) and the Effects Factoring Approach (EFA). A comprehensive numerical study based on the finite element method was carried out to assess the impact on the design of retaining walls in excavations for persistent design situations. Typical wall systems with different support conditions, groundwater levels, excavation depths, and embedment lengths were analysed. Investigations were restricted to homogeneous sand. Overall, it was found that for this type of soil, both verification methods yield similar results for the sectional forces along the wall. The two variants for the MFA were also compared, and the differences arising from the different initial conditions regarding the reduction of the shear strength values are highlighted. It is shown that the required embedment length differs from that computed by numerical methods due to the different stress distributions assumed along the wall and the additional verification of sufficient ground support in the embedded wall portion.

Keywords: excavations; verification; Eurocode 7; finite-element-method

1 INTRODUCTION

The next generation of EN 1997 will include regulations for numerical calculations in conjunction with verifications of serviceability limit states (SLS) and ultimate limit states (ULS). The finite element method (FEM) is commonly applied in practice for this purpose. This article is based on the documents issued at the end of 2022, prEN 1997-1:2022 (CEN, 2022a) and prEN 1997-3:2022 (CEN, 2022b). Details of the different verification methods in conjunction with the FEM and the associated difficulties have been addressed by various authors in the past, e.g. Bauduin et al. (2005), Bond (2013), Brinkgreve and Post (2015), Katsigiannis et al. (2015), Schweiger et al. (2014), Simpson and Hocombe (2010).

For analytical calculations, prEN 1997-1:2022 distinguishes between the Material Factor Approach (MFA) and the Resistance Factor Approach (RFA). For numerical methods, the so-called Effects Factoring Approach (EFA) was introduced to replace RFA. Later, MFA and EFA were renamed to Input and Output factoring approaches, respectively. To avoid ambiguity, we keep the initial designation MFA and EFA. prEN 1997-1 requires that both EFA and MFA be considered, with the less favourable result being decisive. However, EFA must always be linked with some RFA-based verification, and we use here the notation EFA/RFA.

The concept of EFA/RFA is to factor action effects and resistances, which is indirectly taken into account in the material properties, analysis method, and modelling fidelity. Advantages are the comprehensible verification, the constant level of safety, the realistic representation of the subsoil through the use of characteristic parameters, the consideration of safety factors on the water pressures, and the possibility of examining specific failure mechanisms, cf. Smith and Gilbert (2011a, 2011b).

The philosophy of the MFA is to apply the partial safety factors to the dominant uncertainty source, i.e. the material parameters. There are two distinct options: MFA-1, where the analysis is initially performed with characteristic values for the material parameters, and at critical stages, ULS verifications using the respective design values of the material parameters are carried out; MFA-2, where partial factors are applied to the material parameters right from the beginning of the analysis. In prEN1997-1:2022, Table 8.1 MFA-1 corresponds to the recommended option, and MFA-2 to the alternative one.

MFA is straightforward in applying numerical methods when simple constitutive models are adopted, except when considering the effects of groundwater, which are significant in the design of excavation pits. A discussion of both strategies is given by Lees (2017).

It should be mentioned that standard practice in Germany for retaining wall design in excavations assigns this type of structure a transient design situation with lower safety factors. For conciseness, we consider here only persistent design situations.

In the following, the above approaches are applied in the numerical analyses of retaining walls embedded in sand with/without groundwater presence.

2 NUMERICAL STUDY FOR EFA/RFA AND MFA

2.1 *Systems considered*

A total of six different systems were examined with the FEM program Plaxis 2D. Details are given by the authors in Seibel et al. (2022). Four of them are considered herein, cf. Figure 1. For clarity, we keep the systems in the original numbering.

Systems 1 and 2 show sheet pile walls with a single support. The larger embedment length of system 2, denoted by t_1, is selected to represent fixed earth support, whereas t_0 in system 1 is for free earth support.

Systems 5 and 6 represent diaphragm walls chosen to assess the influence of the groundwater. System 5 comprises a deep sealing slab at the level of the wall tip, and the groundwater level difference selected is obtained from the verification against uplift. A groundwater level at the soil surface can only be accommodated by installing an anchored concrete slab, as shown in system 6.

Embedment depths were initially determined from the analytical method according to Blum following the German Recommendations on Excavations EAB (German Geotechnical Society, 2013): t_0 = 2.18 m, t_1= 4.51 m. For system 6, the embedment length is derived for the construction phase with a submerged excavation pit before the installation of the concrete slab: t_2 = 5.17 m.

The soil is modelled to represent medium-dense sand. The built-in Hardening Soil model with non-associated flow rule was selected with the following parameters: friction angle φ_k = 35°, dilatancy angle ψ_k = 10°, unit weight γ = 18 kN/m³, secant stiffness modulus E_{50}^{ref} = 30 MN/m², unloading/reloading stiffness modulus E_{ur}^{ref} = 60 MN/m², stress-level exponent m = 0.77, Poisson's ratio ν = 0.277. Details on the derivation of these parameters are given by Seibel et al. (2022).

For systems 1 and 2, the properties of the wall were taken from Hettler et al. (2006): axial stiffness EA = $4.45 \cdot 10^6$ kN/m, bending stiffness EI = $73.29 \cdot 10^3$ kNm²/m, wall friction angle $|\delta| = (2/3)\varphi_k$. For systems 5 and 6 the respective values were: $EA = 24 \cdot 10^6$ kN/m, $EI = 1.28 \cdot 10^6$ kNm²/m, $|\delta| = (1/2)\varphi_k$.

For the finite-element mesh with 15-node elements the option "fine" was selected; it corresponds to an element length along the wall of approx. 0.4 m. In the last calculation step, after excavating to the final level, a surface load p_k = 10 kPa was applied on the ground surface. Interface elements along the wall were assigned R_{inter} = 1.0, and individual material properties were determined to replicate the wall friction angle defined. The angle of dilatancy is set equal to zero.

For the sake of simplicity, all support elements were given a very high rigidity. For the initial phase before the excavation, the coefficient of earth pressure at rest K_0 was determined using i) the characteristic value of the friction angle for EFA/RFA and MFA-1 and ii) the design value for MFA-2.

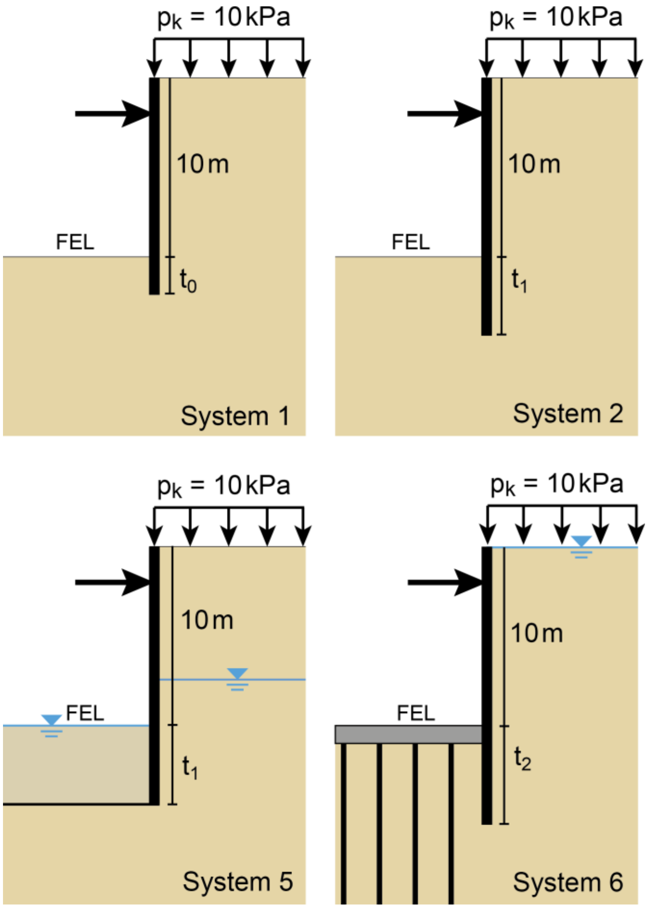

Figure 1. Overview of the models considered (FEL = final excavation level)

2.2 *EFA in combination with RFA (EFA/RFA)*

For EFA/RFA, a calculation with characteristic values was carried out in all phases, and the characteristic values of the sectional forces and soil reactions were determined. Design sectional forces for the verification are obtained by applying the partial safety factor γ_G. Following prEN 1997-3:2022, we set γ_G = 1.35.

2.3 *MFA*

For MFA-1, the analysis is carried out with characteristic soil parameters with additional ULS analysis using reduced soil strength parameters for design-decisive construction stages. Plaxis 2D offers an automated procedure to carry out a so-called safety analysis by gradually reducing the shear strength until system failure occurs. In this study, it is assumed that the friction angle is the value at peak, and hence a target material partial safety factor $\gamma_M = 1.25$ according to prEN 1997-1 was applied to the coefficient of friction tan φ_k yielding the design value $\varphi_d = 29.26°$. The shear strength of the interface elements has been reduced by the same factor, and no partial safety factor has been applied to the dilatancy angle ψ_k.

For MFA-2, the shear strength is a priori reduced accordingly. It should be pointed out that the artificially weakened ground yields an unrealistic system response and may lead to an early, physically not justified failure in an intermediate phase.

The sectional forces determined from the FEM calculation directly represent design parameters for the structural elements (wall, supports).

MFA-1 is the preferred option because both SLS and ULS states can be carried out with a single FEM calculation.

2.4 Embedment length in the FEM models

To verify adequate earth support, as required when adopting the EFA/RFA, the embedment length had to be adjusted. The reason is the different earth pressure distribution compared to the one assumed in the analytical Blum model (German Geotechnical Society, 2013).

For system 1, the embedment length t_0 is obtained by equating the design values of earth support force $B_{h,d}$ and resisting earth pressure force $E_{ph,d}$. The characteristic value $B_{h,k}$ is obtained by integrating the normal stresses along the embedment length. $E_{ph,k}$ is calculated according to DIN 4085:2017-08 (DIN, 2017) with a passive earth pressure coefficient $k_{pgh} = 7.2623$. Applying $\gamma_G = 1.35$ to $B_{h,k}$ and $\gamma_{Re} = 1.4$ to $E_{ph,k}$ yields $B_{h,d} = E_{ph,d}$ for $t_0 = 2.84$ m.

For systems 2, 5 and 6, the embedment length t_1 was not altered since all depths larger than t_0 fulfil the requirement of stable earth support, and t_1 and t_2 merely optimise the wall embedment for a fixed earth support. While in the analytical models, t_1 and t_2 represent fixed earth supports, the different stress distributions in the FEM models may result in a partially fixed support.

3 COMPARISON OF SECTIONAL FORCES

3.1 Systems 1 and 2

Throughout the paper, dotted lines are used for MFA-1 and MFA-2 and solid lines for EFA/RFA. All curves apply to the wall design in the final state with the excavation completed and the surface load applied.

Figure 2 compares design values for bending moments M_d and shear forces Q_d for system 1. The maximum field bending moments are practically the same for EFA/RFA, MFA-1 and MFA-2, with MFA-2 yielding the largest values. Differences are observed along the embedment length, where EFA/RFA - in contrast to MFA - exhibits a very small fixing moment that is not apparent in the analytical solution for hinged support. This is due to the deeper wall embedment in the FEM model compared to the Blum solution. Bear in mind that the embedment length in the FEM is determined by an additional check as outlined in the previous section.

Similarly, Figure 3 displays the results for system 2. As for system 1, the maximum field moments for EFA/RFA and MFA-2 are practically the same, with MFA-2 exhibiting slightly larger values and MFA-1 yielding lower values.

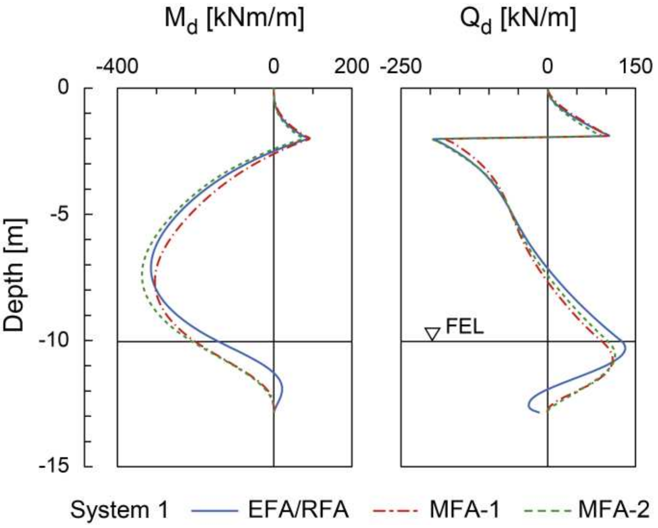

Figure 2. Bending moments M_d and shear forces Q_d for system 1; t_0 = 2.84 m (FEL = final excavation level)

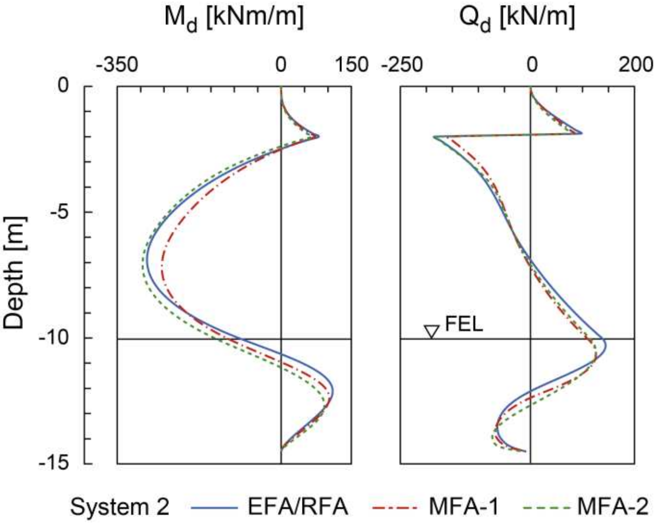

Figure 3. Bending moments M_d and shear forces Q_d for system 2; t_1 = 4.51 m (FEL = final excavation level)

Table 1 summarises for system 2 the calculated maximum field bending moment M_{field} and the maximum bending moment along the embedment length M_{ground} together with their ratio $\alpha_M = M_{field}/M_{ground}$ as an absolute value. It can be seen that within the FEM group of results, MFA-1 yields the smallest α_M. Table 1 includes values obtained by the analytical method of EAB based on beam theory and redistributed earth pressures on the wall, denoted by EAB. Details on the underlying calculation/methodology are given by Seibel et al. (2022). The resulting value α_M = 1.05, i.e. field moment and ground support moment are very similar, leading to a more economical wall design. At the same time, the smaller bending moments in the ground support predicted by the FEM analyses may lead to an unsafe design in the case of diaphragm walls.

Table 1. Maximum bending moments in the field and in the ground support for system 2

Method	M_{field} [kNm/m]	M_{ground} [kNm/m]	$\lvert\alpha_M\rvert$
EFA/RFA	286	-110	2.60
MFA-1	255	-103	2.48
MFA-2	296	-92	3.22
EAB	207	-197	1.05

3.2 Systems 5 and 6

Figures 4 and 5 show the response of the single supported system under the effect of groundwater pressures (systems 5 and 6). The lack of a safety factor on the water pressures can be seen in the bending moment distribution. For system 5, EFA/RFA and MFA-2 yield similar curves (maximum values 864 and 792 kNm/m, respectively); MFA-1 shows considerably lower values with a difference of approx. 30% in the maximum values (maximum value for MFA-1 equal to 624 kNm/m).

Differences are also observed for system 6 with EFA/RFA exhibiting for the maximum field bending moment approx. 27% higher values than MFA-1 and MFA-2 (914 kNm/m compared to 682 kNm/m for MFA-1 and 757 kNm/m for MFA-2). For this particular case, EFA/RFA would be the relevant verification approach for the design.

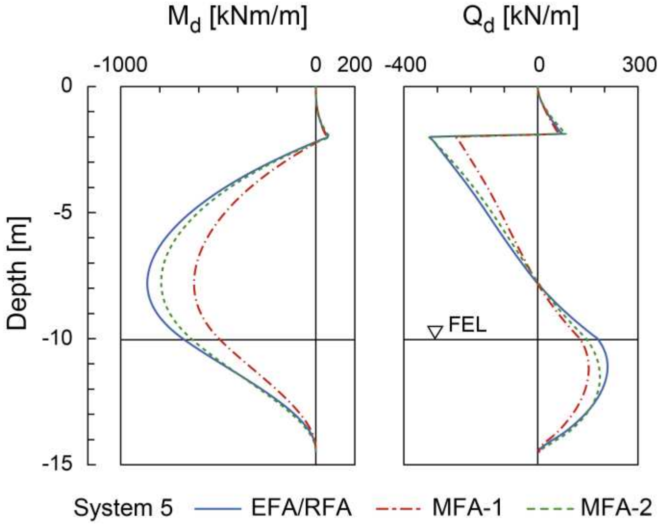

Figure 4. Bending moments M_d and shear forces Q_d for system 5; t_1 = 4.51 m (FEL = final excavation level)

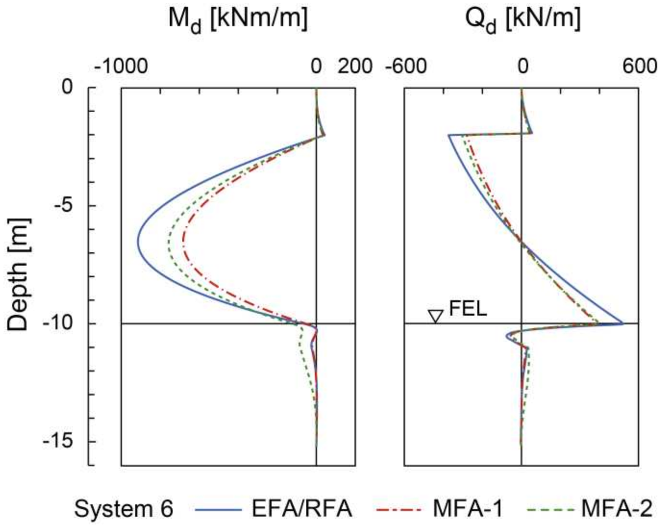

Figure 5. Bending moments M_d and shear forces Q_d for system 6; t_2 = 5.17 m (FEL = final excavation level)

4 CONCLUSIONS

The FEM analyses showed that in most cases there is little or negligible difference between EFA/RFA and MFA, at least for the geometry and soil considered. When water pressures are involved, the missing safety factor for its effects in the MFA becomes apparent, and EFA/RFA is design-relevant.

In some cases, there are significant differences between the MFA-1 and MFA-2, with MFA-1 yielding lower values for the sectional forces.

For single-supported walls with embedment length corresponding to a partially or fully fixed earth support according to Blum (system 2), the soil restraining effect can be underestimated when using MFA. In MFA, the soil resistance along the embedment length is weakened, and the field moment increases due to a stress redistribution within the system, see also Table 1.

It should be noted that the findings of the study apply to relatively high-strength sand, and separate investigations are required for softer soils.

Open questions concerning the MFA refer to the influence of the initial stresses, expressed by K_0, on the sectional forces and the definition of a suitable partial safety factor to account for the effects of groundwater pressures.

5 REFERENCES

Bauduin, C., Bakker, K.J., Frank, R. 2005. Use of finite element methods in geotechnical ultimate limit state design. *Proceedings, 16th International Conference on Soil Mechanics and Geotechnical Engineering*, 2775-2779.

Bond, A. 2013. Implementation and evolution of Eurocode 7. *Modern Geotechnical Design Codes of Practice* (Eds: Arnold, P. et al.), 3-14. IOS Press, Amsterdam.

Brinkgreve, R.B.J., Post, M. 2015. Geotechnical ultimate limit state design using finite elements. *Geotechnical Safety and Risk V* (Eds: Schweckendiek, T. et al.), 464-469. IOS, Amsterdam.

CEN - European Committee for Standardization 2022a. pr EN 1997-1:2022 Draft, Eurocode 7: Geotechnical design — Part 1: General rules.

CEN - European Committee for Standardization 2022b. pr EN 1997-3:2022 Draft, Eurocode 7: Geotechnical design — Part 3: Geotechnical structures.

DIN - German Institute for Standardization 2017. DIN 4085:2017-08, Subsoil - Calculation of earth-pressure.

German Geotechnical Society 2013. *Recommendations on Excavations - EAB, 3rd Edition*. Ernst & Sohn, Berlin.

Hettler, A., Vega Ortiz, S., Mumme, B. 2009. Calculation of excavation walls with different methods: Girder model, non-linear subgrade reaction model, finite-element analysis, *Bautechnik* **86**, 54-63.

Katsigiannis, G., Schweiger, H.F., Ferreira, P., Fuentes, R. 2015. Design of deep supported excavations: comparison between numerical and empirical methods. *Geotechnical Safety and Risk V* (Eds: Schweckendiek, T. et al.), 479-485. IOS, Amsterdam.

Lees, A.S. 2017. Use of geotechnical numerical methods with Eurocode 7. *Proceedings of the Institution of Civil Engineers - Engineering and Computational Mechanics*, **170**, 4, 146–153.

Plaxis 2D Connect Edition V21 – Finite element code for soil and rock analyses, Bentley Systems.

Schweiger. H.F. 2014. Influence of EC7 design approaches on the design of deep excavations with FEM, *geotechnik* **37**, 169–176.

Seibel, E., Vrettos, C., Hettler, A. 2022. Bewertung der Nachweiskonzepte nach EC7 für Baugrubenwände in Sand auf Grundlage der Finite-Elemente-Methode, *Bautechnik* **99**, 865-877.

Simpson, B., Hocombe, T. 2010. Implications of modern design codes for earth retaining structures. *Proceedings, 2010 Earth Retention Conference*.

Smith, C., Gilbert, M. 2011a. Ultimate limit state design to Eurocode 7 using numerical methods, part 1: methodology and theory. *Ground Engineering* **44**, 10, 25-30.

Smith, C., Gilbert, M. 2011b. Ultimate limit state design to Eurocode 7 using numerical methods, part 2: proposed design procedure and application. *Ground Engineering* **44**, 11, 24-29.