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Reliability Assessment of Eurocode 7 Retaining Structures Design Methodology

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ABSTRACT: This paper is a contribution for the application of Eurocode 7 design methodology, based on the limit state design (LSD) approach. The design methodology of Eurocode 7 is applied to a concrete gravity retaining structure resting on a relatively homogeneous c-φ soil, and the different design approaches are compared to deterministic and semi-probabilistic solutions, considering the bearing resistance failure of the foundation. A reliability assessment is performed for different conditions, selecting different geotechnical parameters, particularly characteristic values and coefficients of variation of soil properties, and taking into account the effects of vertical fluctuation scale by using a simplified approach. Several uncorrelated and correlated random variables are considered, and probabilistic solutions are achieved and compared with a target ultimate limit state reliability index β for a medium risk structure and fifty years reference period, considered as 3.8. For this purpose, reliability techniques such as the first-order reliability method (FORM) and the Monte Carlo simulation (MCS) are applied and compared to other methodologies. Based on the obtained results, the Eurocode 7 design methodology is discussed, and the indispensable engineering judgment is outlined.

Keywords: Eurocode 7; limit state design; retaining structures; reliability; variability

1 INTRODUCTION

The Eurocodes are a set of European Standards for the design of buildings and other civil engineering works, based on the limit state design (LSD) approach, used in conjunction with a partial factor methodology. A wide range of types of structures and products is covered and moreover, the harmonization of safety levels in construction is a contribution to improve the competitiveness of the construction industry in the global markets. In this context, the adoption of Eurocodes may be attractive worldwide, also outside European Union, taking into account the flexibility provided by a system of nationally determined parameters.

Eurocode 7 is a geotechnical design code that shares common bases with the design methodology for structures, consisting of two parts: EC 7-1 (General rules) and EC 7-2 (Ground investigation and testing). The design approaches and the values of the partial factors are specified by each Member State in a National Annex, and extensive education and training is required in implementation towards harmonization. In the long term, matters relating to the development of new items will be examined, for example harmonization of calculation methods or evaluation of test results with respect to the selection of characteristic values of soil properties. According to this, research is strongly encouraged for further harmonization of geotechnical design in European Union: the values of recommended partial factors have been based largely on reproducing existing designs, with traditional levels of safety and sustainability, and further investigation about economic issues is therefore relevant; other practical interest is the application of numerical methods in addition to the classical calculation models (Schuppener, 2010).

It may be argued that comparative studies of the different design approaches and values of the partial factors are required for harmonization, thus further research about reliability assessment of Eurocode 7 design methodology is a promising and valuable contribution for the development of insight, allowing the acquirement of new skills. According to this, partial results of a study concerning Eurocode 7 design methodology and reliability are introduced in this paper. Design concepts of Eurocode 7 with regard to retaining structures on a relatively homogeneous c-φ soil are presented, and a reliability-based design (RBD), level I and level II, is performed by selecting different geotechnical parameters, particularly characteristic values and coefficients of variation of soil properties. For this purpose, several uncorrelated and correlated random variables are considered. The effects of vertical fluctuation scale are accounted considering different vertical spatial correlation lengths, even as vertical characteristic lengths. Finally, different methodologies for reliability evaluation are compared, and the influence of probability distribution is also outlined.

2 CHARACTERISTIC VALUES

The estimation of characteristic values depends on risk tolerance, in other words, affects stability as well as economic feasibility, and shall be based on the results of field and laboratory tests. This means that a clear definition of characteristic values is essential. Characteristic values are representative values of parameters, evaluated by considering uncertainties, and considered as the most adequate values to estimate the occurrence of limit states. Due to genetic and anthropogenic processes, soil is nonhomogeneous regarding its geometrical and physical characteristics, wherefore soil properties are predicted through models. Even so, the spatial variability of soil properties in a relatively homogeneous layer may be broad and affect significantly the reliability of geotechnical systems. Therefore, the investigation concerning characteristic values provides very valuable insights into reliability-based design (RBD), and an important issue is the soil variability owing to insufficient test data (Yoon *et al.*,2010).

This paper presents results based on the definition of eight sets of characteristic values of soil properties X_k - pure mean values (considered as a superior reference) (1), Schneider's equation values (2), Ovesen's equation values (3), 95% reliable mean values (according to the number of test results and for unknown or known Cv_x, referenced as mean) (4), 5% fractile values (from a normal probability distribution) (5), and 5% fractile values (according to the number of test results and for unknown or known Cv_x, referenced as low) (6):

$X_k=X_m$ (1); $X_k=X_m-0.5\sigma_x$ (2); $X_k=X_m-1.645\sigma_x/\sqrt{N}$ (3);

$X_k=X_m(1-k_{n,mean}Cv_x)$ (4); $X_k=X_m-1.645\sigma_x$ (5); $X_k=X_m(1-k_{n,low}Cv_x)$ (6)

in which X_m is the mean value, σ_x is the standard deviation, Cv_x is the coefficient of variation, N is the number of test results, and $k_{n,mean}$ and $k_{n,low}$ are statistical coefficients taking into account the sampling (only local, when Cv_x is considered unknown, or local in conjunction with relevant experience, when Cv_x is considered known), the number of test results, the value affecting the occurrence of the limit state (the mean value, or the lowest value, respectively), and the statistical level of confidence required for the assessed characteristic value, expressed by a considered t factor of Student's distribution (Frank *et al.*, 2004; Yoon *et al.*, 2010). A relatively homogeneous soil and normal probability distributions for the values of soil properties were assumed, although this assumption is not always valid (for the considered example, all characteristic values of soil properties yield positive results). Characteristic load values were considered as 95% fractile values (from a normal probability distribution).

3 EXAMPLE

A concrete gravity retaining structure is shown in Figure 1. For bearing capacity predictions (inclined eccentric loading problem) the performance function can be described by the simplified equation (7):

$$M = f(B_1, B_2, H_1, H_2, \gamma_c, \varphi_w, \gamma_w, c_f, \varphi_f, \gamma_f, q) \quad (7)$$

where the sum of B_1 and B_2 is the foundation width B; H_1 is the wall height; H_2 is the foundation height; γ_c is the unit concrete weight; φ_w is the friction angle of the soil on the active and passive sides of the wall; γ_w is the unit soil weight on the active and passive sides of the wall; c_f is the cohesion of the foundation soil; φ_f is the friction angle of the foundation soil; γ_f is the unit weight of the foundation soil; and q is the variable surcharge at ground surface. Other considered parameters are: the soil-wall interface friction angle on the active side of the wall $\delta_w a = 2/3\,\varphi_w$; and the soil-wall interface friction angle on the passive side of the wall $\delta_w p = 0$.

Table 1 summarizes the data based on the results of some tests on a c-φ soil or published values in the literature, where the coefficient of variation is both considered unknown or known (some references are Cherubini, 2000; Duncan, 2000; Forrest *et al.*, 2010; Phoon *et al.*, 1999a; Phoon *et al.*, 1999b).

The effects of spatial variability are accounted by the approach described by equation (8):

$$\Gamma^2 = \left[\frac{\theta_v}{L_v}\left(1 - \frac{\theta_v}{4L_v}\right)\right] \text{ for } \frac{\theta_v}{L_v} \leq 2 \qquad (8)$$

where Γ is the variance reduction factor; θ_v is the vertical spatial correlation length; and L_v is the vertical characteristic length, related to the dimensions of the potential failure surface (VanMarcke, 1983).

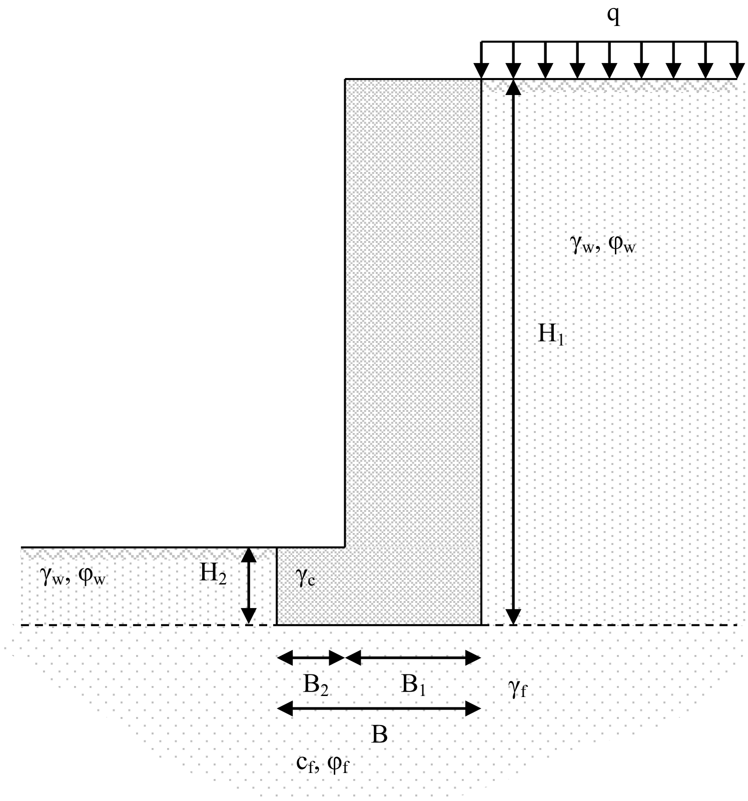

Figure 1.Concrete gravity retaining structure.

Table 1.Data based on the results of some tests on a c-φ soil or published values in the literature.

Basic random variables	Probability distribution	Number of test results	Mean value μ	Standard deviation σ	Coefficient of variation Cv
B_1 (m)	Normal	-	-	-	0.04
B_2 (m)	Normal	-	1.00	0.04	0.04
H_1 (m)	Normal	-	7.00	0.28	0.04
H_2 (m)	Normal	-	1.00	0.04	0.04
γ_c (kN/m³)	Normal	-	24.00	0.96	0.04
φ_w (°)	Normal	5	33.00	2.4495[a] μ*Cv[b]	0.0742[a] 0.10[b]
γ_w (kN/m³)	Normal	5	18.80	0.8367[a] μ*Cv[b]	0.0445[a] 0.05[b]
c_f (kN/m²)	Normal Lognormal	5	14.00	4.1833[a] μ*Cv[b]	0.2988[a] 0.20;0.40;0.60[b]
φ_f (°)	Normal	5	32.00[a,b] 25.00;30.00;35.00;40.00[b]	2.3452[a] μ*Cv[b]	0.0733[a] 0.05;0.10;0.15[b]
γ_f (kN/m³)	Normal	5	17.80	0.8367[a] μ*Cv[b]	0.0470[a] 0.05[b]
q (kN/m²)	Normal	-	10.00	2.50	0.25

[a]Coefficient of variation unknown, obtained from the results of some tests on a c-φ soil.
[b]Coefficient of variation known, obtained from published values in the literature; central values of Cv are recommended values and were generally used (exception for Figures 7 and 8); φ_f=32.00 (exception for Figure 9).

4 RESULTS

Based on the definition of eight sets of characteristic values of soil properties X_k, the minimum foundation width B was determined for the different Design Approaches of Eurocode 7: DA.1.1 (Design Approach 1 Combination 1, essentially a STR limit state approach), DA.1.2 (Design Approach 1 Combination 2, essentially a GEO limit state approach), DA.2 (Design Approach 2, an action and resistance factor approach, partial factors applied to the ground resistance and to the actions), DA.2* (Design Approach 2, an action and resistance factor approach, partial factors applied to the ground resistance and to the effects of actions), and DA.3 (Design Approach 3, an action and material factor approach); a similar foundation width B is derived for DA.1.2 and DA.3; the design for DA.1 is governed by DA.1.2; partial factors from Annex A of EC 7-1.

Figures 2 and 3 show respectively, the characteristic values of soil properties X_k based on the definition of eight sets, and the corresponding foundation width B, for the different Design Approaches DA.1.1, DA.1.2, DA.2, DA.2*, and DA.3. According to Table 1, the different foundation widths $B=B_1+B_2$ are derived from a variable B_1, considering a single B_2, and performing the vertical equilibrium for the inclined eccentric loading problem with regard to bearing capacity predictions.

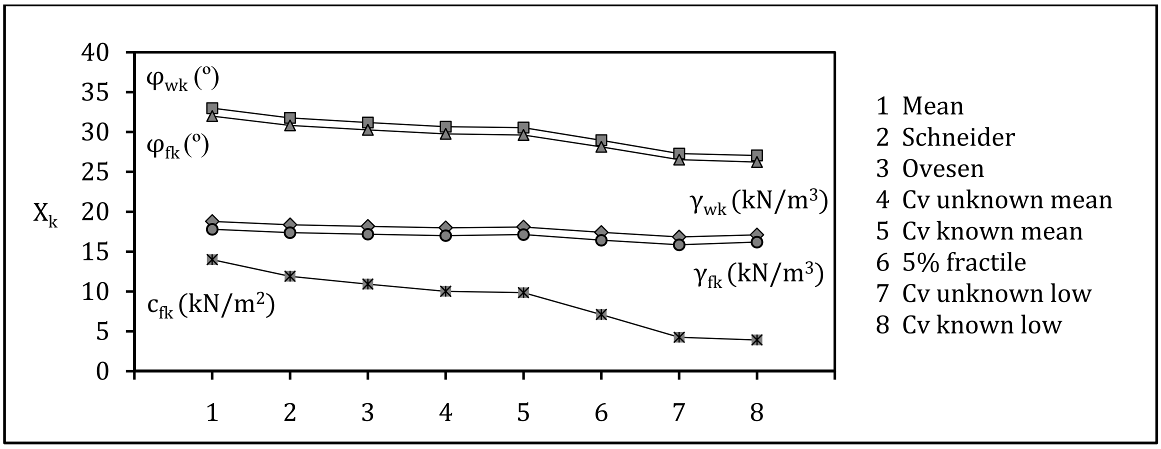

Figure 2.Characteristic values of soil properties X_k based on the definition of eight sets.

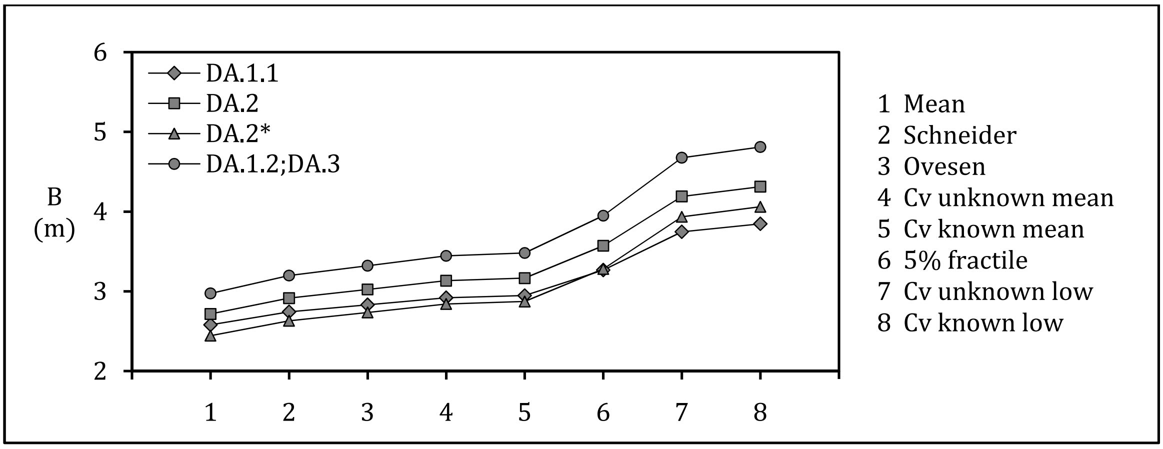

Figure 3.Foundation width $B=B_1+B_2$ based on the definition of eight sets of X_k for the different Design Approaches DA.1.1, DA.1.2, DA.2, DA.2* and DA.3.

Based on the definition of eight sets of X_k, the mean factor of safety Fs_m and the characteristic factor of safety Fs_k, described respectively by equations (9) and (10), are shown in Figures 4 and 5 for the different Design Approaches DA.1.1, DA.1.2, DA.2, DA.2* and DA.3. The characteristic resistance is computed by geotechnical formulas using conservative estimates of the soil properties, namely characteristic values, while the characteristic load is the sum of conservative unfactored estimates of characteristic load actions acting on the system; Fs_m is derived when the mean values are considered as characteristic values.

$$Fs_m = \frac{\text{mean resistance}}{\text{mean load}} \quad (9); \quad Fs_k = \frac{\text{characteristic resistance}}{\text{characteristic load}} \quad (10)$$

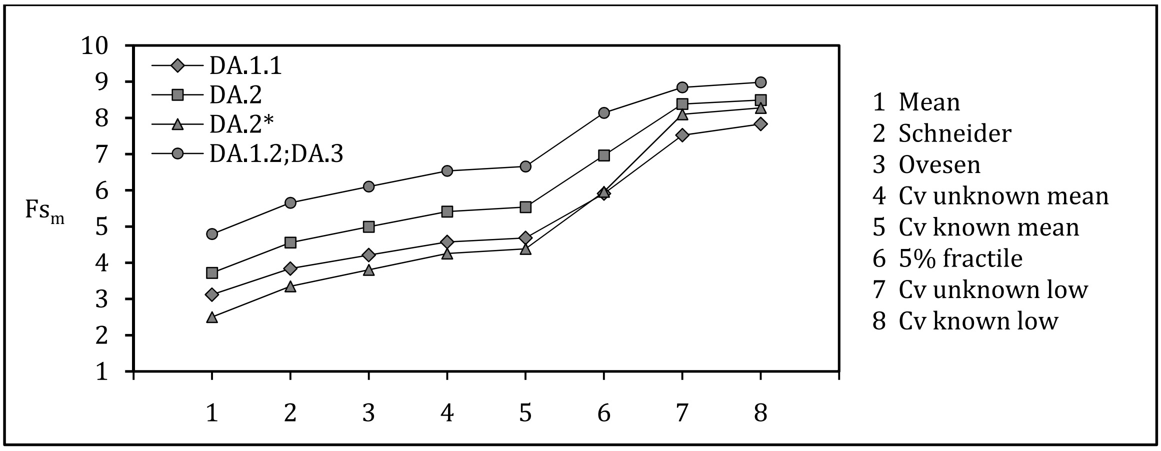

Figure 4.Factors of safety Fs_m based on the definition of eight sets of X_k for the different Design Approaches DA.1.1, DA.1.2, DA.2, DA.2* and DA.3.

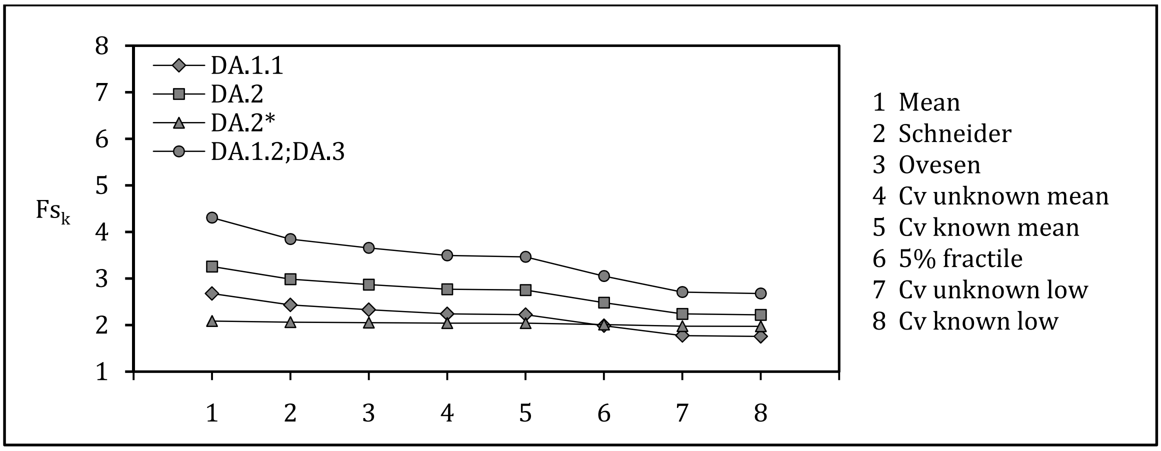

Figure 5.Factors of safety Fs_k based on the definition of eight sets of X_k for the different Design Approaches DA.1.1, DA.1.2, DA.2, DA.2* and DA.3.

Reliability assessment was performed considering normal and lognormal probability distributions, but according to the estimation of characteristic values, the results introduced in this paper are based essentially on normal probability distributions for all basic random variables, with exception to the parameter c_f, normal or lognormal, for comparative study. Therefore, based on the definition of eight sets of X_k, the reliability index β obtained by FORM method (minimizing), considering c_f normal or lognormal and uncorrelated random variables, is shown in Figure 6 for the different Design Approaches DA.1.1, DA.1.2, DA.2, DA.2* and DA.3 (target ultimate limit state reliability index β=3.8).

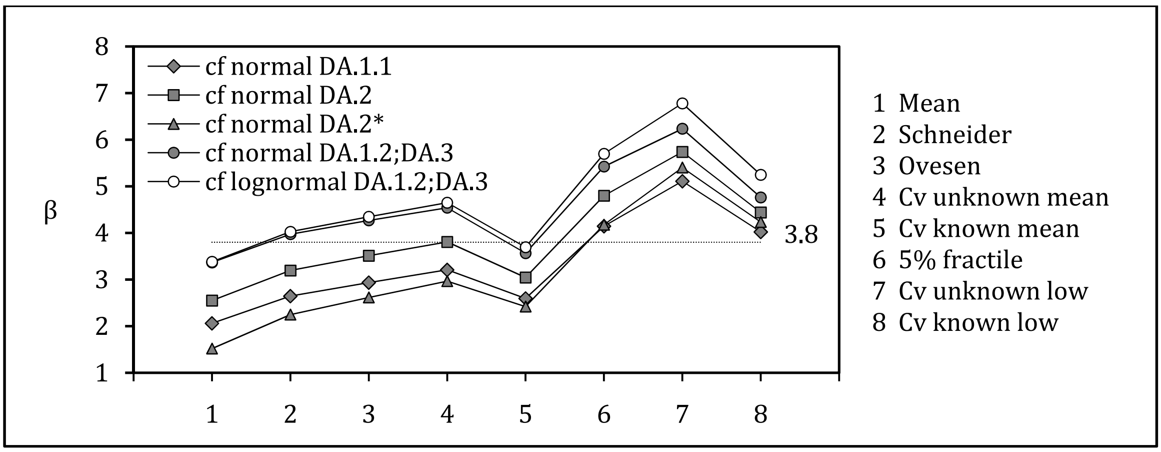

Figure 6.Reliability index β based on the definition of eight sets of X_k, obtained by FORM method (minimizing) considering c_f normal or lognormal and uncorrelated random variables, for the different Design Approaches DA.1.1, DA.1.2, DA.2, DA.2* and DA.3.

The reliability index β obtained by FORM method (minimizing), considering different coefficients of variation of c_f and φ_f or different friction angles of the foundation soil φ_f, is shown in Figures 7 and 8 or 9, respectively (target ultimate limit state reliability index β=3.8). The case Cv known mean was considered for the different Design Approaches DA.1.1, DA.1.2, DA.2, DA.2* and DA.3.

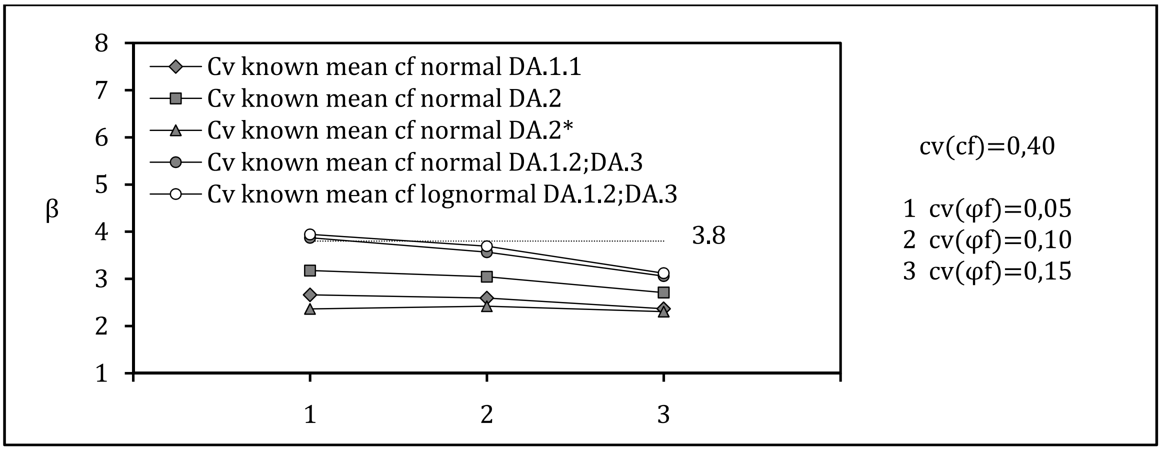

Figure 7.Reliability index β for the case Cv known mean, obtained by FORM method (minimizing) considering c_f normal or lognormal and different coefficients of variation of c_f and φ_f (uncorrelated random variables), for the different Design Approaches DA.1.1, DA.1.2, DA.2, DA.2* and DA.3.

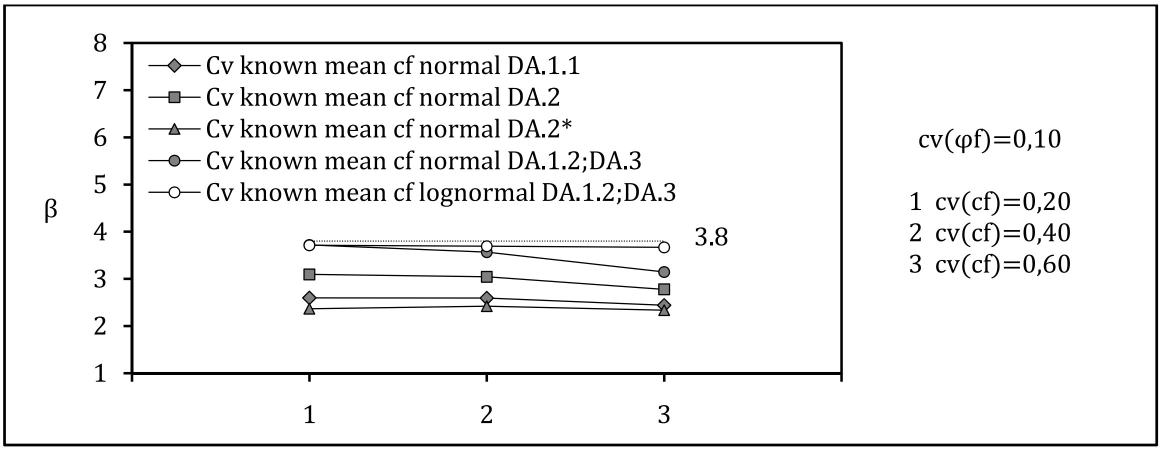

Figure 8.Reliability index β for the case Cv known mean, obtained by FORM method (minimizing) considering c_f normal or lognormal and different coefficients of variation of c_f and φ_f (uncorrelated random variables), for the different Design Approaches DA.1.1, DA.1.2, DA.2, DA.2* and DA.3.

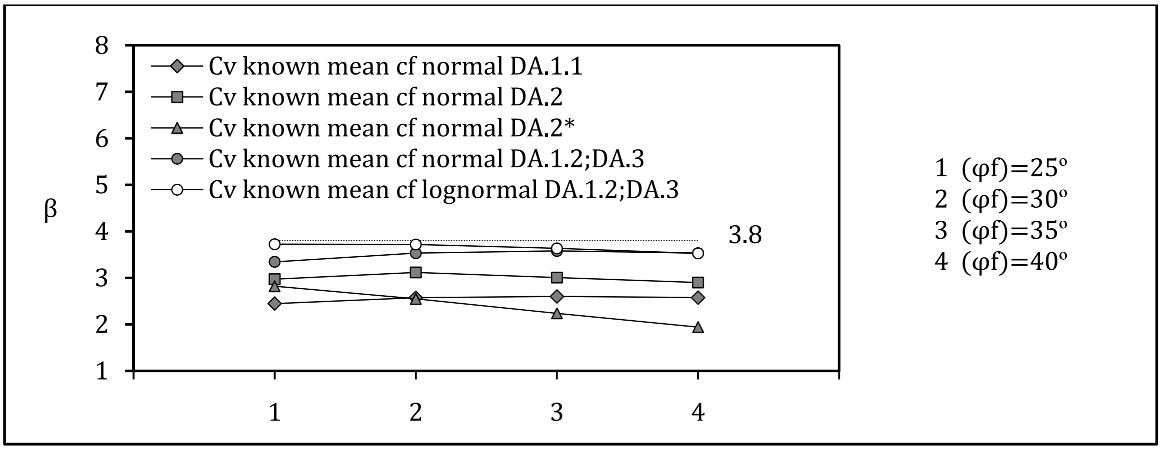

Figure 9.Reliability index β for the case Cv known mean, obtained by FORM method (minimizing) considering c_f normal or lognormal and different friction angles of the foundation soil φ_f (uncorrelated random variables), for the different Design Approaches DA.1.1, DA.1.2, DA.2, DA.2* and DA.3.

The influence of correlation between c_f and φ_f is illustrated in Figure 10 for the Design Approaches DA.1.2 and DA.3, considered the cases Schneider, Ovesen, Cv unknown mean and Cv unknown low.

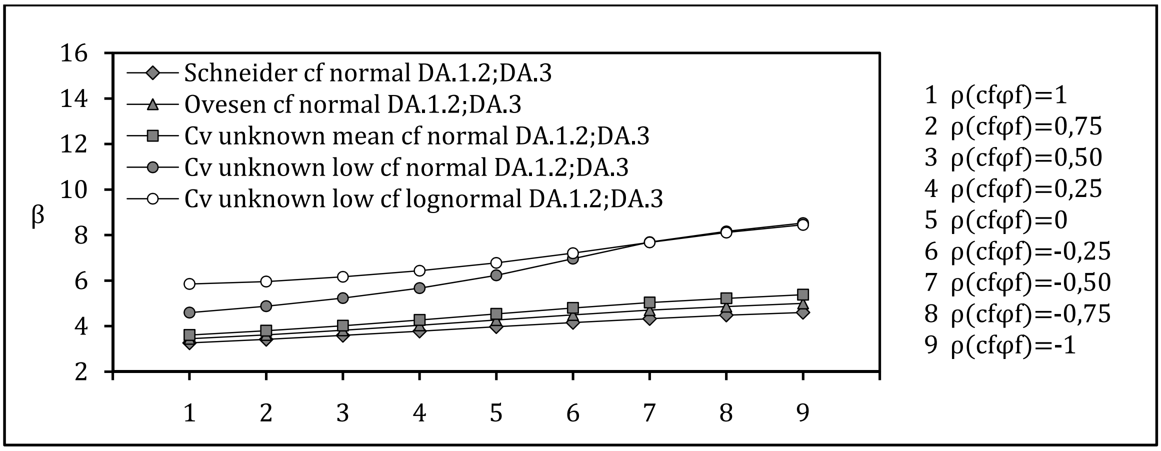

Figure 10.Reliability index β for the cases Schneider, Ovesen, Cv unknown mean and Cv unknown low, obtained by FORM method (minimizing) considering c_f normal or lognormal and different coefficients of correlation between c_f and φ_f, for the Design Approaches DA.1.2 and DA.3.

The influence of spatial variability of soil properties is illustrated in Figure 11 for the Design Approaches DA.1.2 and DA.3, considered the case Cv known mean, for different vertical spatial correlation lengths θ_v and vertical characteristic lengths $L_v=H_2+B$ or $L_v=H_2+1.8*B$ (target ultimate limit state reliability index β=3.8).

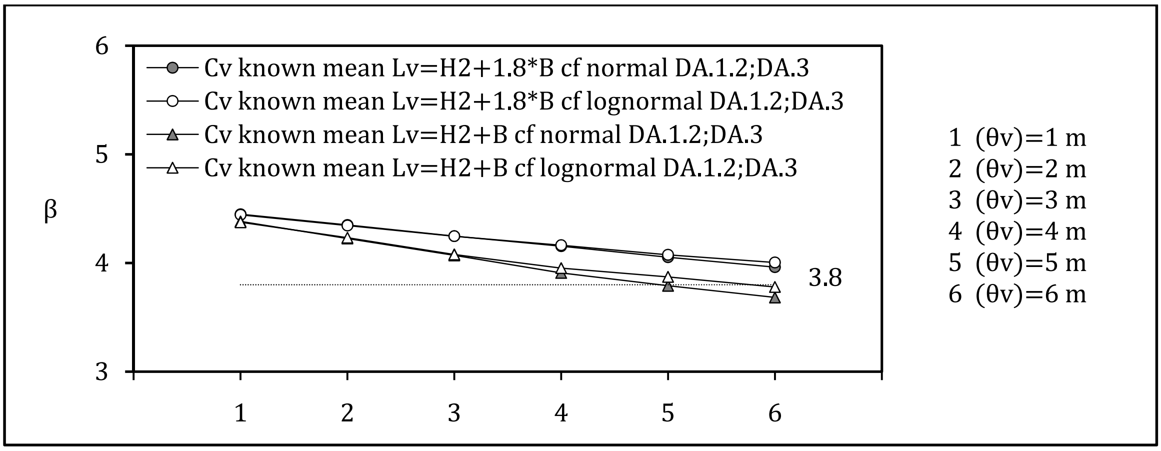

Figure 11.Reliability index β for the case Cv known mean, obtained by FORM method (minimizing) considering c_f normal or lognormal and different vertical spatial correlation lengths θ_v, even as vertical characteristic lengths $L_v=H_2+B$ or $L_v=H_2+1.8*B$ (uncorrelated random variables), for the Design Approaches DA.1.2 and DA.3.

The reliability index β obtained by different methodologies for the Design Approaches DA.1.2 and DA.3, considered the case Mean, for c_f normal and uncorrelated random variables, is shown in Figure 12.

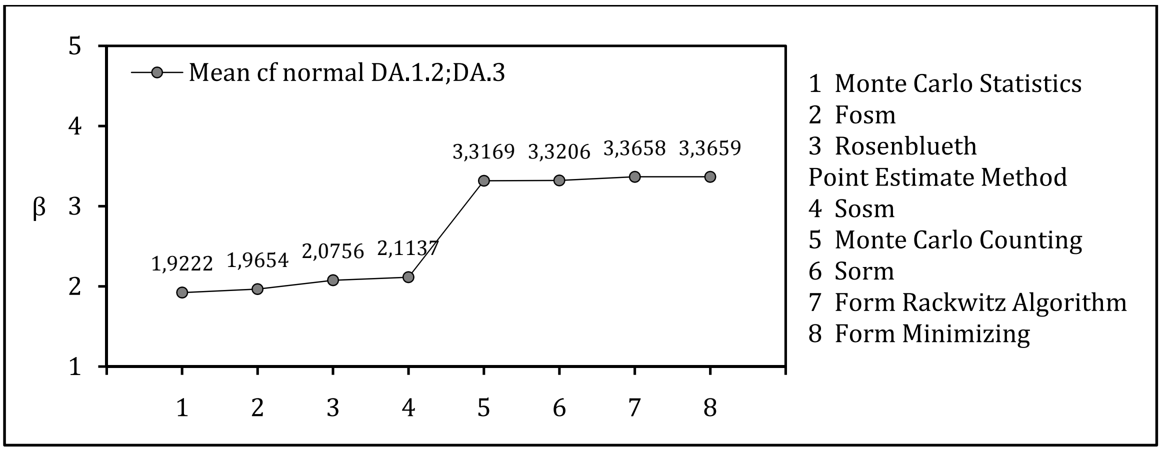

Figure 12.Reliability index β for the case Mean, obtained by different methodologies considering c_f normal and uncorrelated random variables, for the Design Approaches DA.1.2 and DA.3 (MCS results from 24 simulation runs, each one with 3000000 simulation steps; MCS failure probability percentage error 1.1%).

5 DISCUSSION

Based on the definition of eight sets of characteristic values of soil properties X_k, and for the partial factors recommended in Annex A of EC 7-1 for the three Design Approaches, the minimum foundation width B is variable from: 3.20 m to 4.81 m for the Design Approaches DA.1 and DA.3; 2.92 m to 4.31 m for the Design Approach DA.2; and 2.63 m to 4.06 m for the Design Approach DA.2* (case Mean excluded). According to this, the estimation of characteristic values is a determinant issue when analyzing considerable differences in geotechnical design, and moreover, the selected design approaches and values of the partial factors specified by each Member State may be somewhat variable. Therefore, it may be argued that a more formal basis for the exercise of engineering judgment is required, particularly, the value of analysis is considerably enhanced when a complementary reliability assessment is performed.

Considered an acceptable overall factor of safety between 2 and 3, Fs_m or Fs_k, the corresponding reliability index β for the considered design approaches is variable, sometimes lower or even much higher than 3.8, the target ultimate limit state reliability index β for a medium risk structure (reliability class RC2, according to NP EN 1990:2009) and fifty years reference period. Model parameters as dimensions derived from the choice of characteristic values, and coefficients of variation or correlation of soil properties are relevant when comparing solutions, as well as the wide range of geotechnical parameters. According to some results, the friction angle of the foundation soil, φ_f, was considered variable from 25º to 40º and sensitivity analysis point out φ_f as one of the most important parameters concerning reliability, as shown in Figure 7. The effects of spatial variability are favourable, but dependent on θ_v, the vertical spatial correlation length, and L_v, the vertical characteristic length, related to the dimensions of the potential failure surface and considered in the literature between H_2+B and H_2+2*B: according to Figure 11, for $\theta_{v=}6$ m and $L_v=H_2+B$, the target ultimate limit state reliability index β is not achieved. The influence of probability distribution is another important item, and results from different methodologies for reliability evaluation may be quite differing, as illustrated in Figure 12 (Haldar *et al*., 2000).

6 CONCLUSION

Further harmonization of geotechnical design in European Union is required in the future to improve the competitiveness of the construction industry and promote sustainable development (Schuppener, 2010). More research about reliability assessment of Eurocode 7 design methodology, based on classical calculation models or application of numerical methods, can yield precious new insights into economic issues by considering the optimization of resources when comparing probabilistic solutions with a target limit state reliability index β: mainly for complex problems, the decision-making process is improved when analyzing considerable differences in geotechnical design. This paper still demonstrates that risk and reliability are complementary, depending on the considered analysis model, and that engineering judgment is essential for the selection of reliable characteristic values for geotechnical design.

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