ISGSR 2011 - Vogt, Schuppener, Straub & Bräu (eds) - © 2011 Bundesanstalt für Wasserbau ISBN 978-3-939230-01-4

Application of reliability based design (RBD) to Eurocode 7

T. Hara, Y. Honjo, Y. Otake & S. Moriguchi
Gifu University, Gifu, Japan

ABSTRACT: This study aims to discuss harmonization of Design Approaches in Eurocode 7 and National Annexes from the viewpoint of reliability. Relative reliability difference of the different design results, which are estimated from respective Eurocode 7 Design Approaches, DA1, DA2, DA3, and National Annexes, with respect to a design example is studied based on the results of level III reliability based design, and several issues concerning reliability are discussed in this paper.

Keywords: Eurocode 7, Partial factor, Reliability based design

1 INTRODUCTION

The developments of design codes grounded on the reliability based design (RBD) are actively taking place in various part of the world today. RBD is considered to become the central tool of the design code developments. We consider it desirable that Eurocode 7 (EC7), which is recognized as one of the most important geotechnical design codes in the world, would introduce this concept and stand on the same ground. The introduction of RBD would provide useful information for the development of Design Approaches (DAs) and National Annexes (NAs), which is one of the central tasks EC7 is now encountering. It would also facilitate the harmonization of EC7 to other structural Eurocodes as well as other geotechnical design codes in the world, because once reliability (i.e. a quantified measure of the structure performances) become a common language, we would obtain common ground for communication.

Recognizing these backgrounds, this study focused on the different design results depending on respective DAs and NAs, which were presented in the 2nd International workshop of ETC10 in Pavia in April 2010. In this paper, the relative reliability difference of the different design results with respect to a design example is studied from a comparison with results of a level III RBD, and several issues concerning reliability are discussed.

2 PRCEDURE FOR THIS STUDY

In this study, as shown in Figure 1, EC7 based design and a level III RBD on a design example are carried out at first, and the relative reliability level difference is studied from the relationship between reliability levels and foundation dimensions, which were obtained from the RBD. Finally, future issues on EC7 that is discussed based on the study done in the first part: determination of partial factors based on target reliability and code calibration of NAs are discussed.

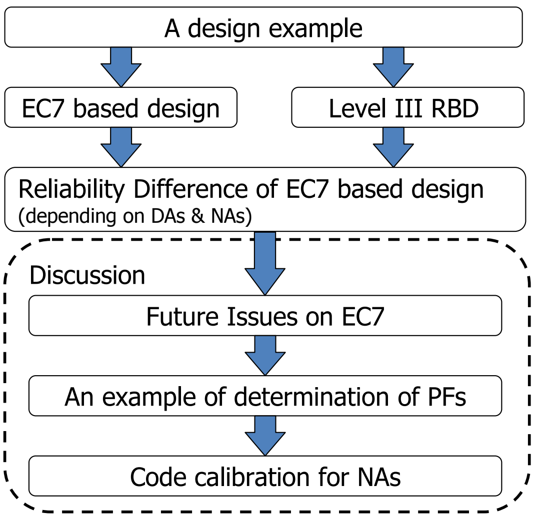

Figure 1. Procedure for this study

3 EC7 BASED DESIGN AND THE RELIABILITY

3.1 *Target Design Example*

The target design example is one to determine the width of a square pad foundation on a uniform and very dense fine glacial out wash sand layer of 8m thick on the underlying bedrock, as shown in Figure 2, which is one of the six examples set by ETC10 in Pavia in 2010 (ETC10 2010). In this example in the ETC10, both stability and serviceability, which the settlement should be less than 25mm, are required. In this section, mainly stability as Ultimate Limit State (ULS) is focused. Different design results of Serviceability limit State (SLS), which were estimated by respective NAs, are described in the ETC10. The necessity of partial factor for SLS design is also discussed in the subsequent section.

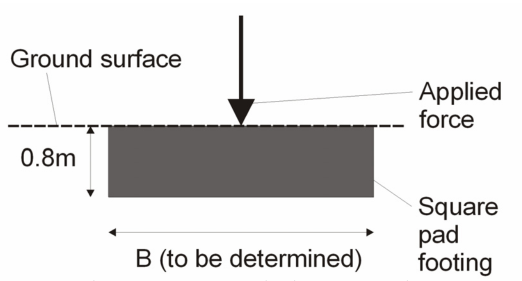

Figure 2. Target design example.

In the given condition of the design example, the pad foundation is to be built at embedded depth of 0.8m, and vertical permanent and variable loads of the characteristic values 1000kN (excluding weight of the foundation) and 750kN are respectively applied. Four CPT test results within 15m radius from the point, where the pad foundation is to be constructed, and digitized q_c and f_s values of 0.1m interval are given from the ground surface to 8m depth. The groundwater is at 6m depth from the ground surface and the unit weight of sand of 20kN/m^2 are also specified.

3.2 *EC7 Based Design*

The recommended characteristic values of the foundation ground presented in the ETC10 workshop by Sorensen et al. (2010), are shown in Table 1, which are based on the specifications of EC7. These values are adopted in the EC7 based design of this study. Design equations and partial factors, which are quoted from EN1997-1 Annex A, D and the 1st ETC10 report (Orr 2005), are presented in equation (1), (2) and Table 2, respectively.

$$\mathrm{V_d} = \gamma_\mathrm{G} \cdot \left(\mathrm{G_k} + \gamma_\mathrm{c} \cdot \mathrm{A} \cdot \mathrm{d}\right) + \gamma_\mathrm{Q} \cdot \mathrm{Q_k} \tag{1}$$

$$\mathrm{R_d} = \mathrm{A'} \cdot \left(\mathrm{q'} \cdot \mathrm{N_q} \cdot \mathrm{s_q} + 0.5 \cdot \gamma' \cdot \mathrm{B'} \cdot \mathrm{N}_\gamma \cdot \mathrm{s}_\gamma\right) / \gamma_\mathrm{R} \tag{2}$$

$$\mathrm{N_q} = \mathrm{e}^{\pi \cdot (\tan\phi'/\gamma_\mathrm{M})} \cdot \tan^2\left[\pi/4 + \left\{\tan^{-1}\left(\tan\phi'/\gamma_\mathrm{M}\right)\right\}/2\right], \quad \mathrm{N}_\gamma = 2 \cdot \left(\mathrm{N_q} - 1\right) \cdot \left(\tan\phi'/\gamma_\mathrm{M}\right)$$

$$\mathrm{s_q} = 1 + \sin\left\{\tan^{-1}\left(\tan\phi'/\gamma_\mathrm{M}\right)\right\}, \quad \mathrm{s}_\gamma = 0.7$$

where, A and A' are the total and effective area of the foundation (= B^2 in this case) respectively, γ_c is unit weight of RC, B' is effective width (B' = B in this case), s_q and s_γ are shape factors for N_q and N_γ, q' is effective overburden pressure at the level of the foundation base.

Table 1. Proposed characteristic design value (Sorensen et al. 2010)

Layer no.	Depth (m)	Mean depth (m)	$q_{c,m}$ (MPa)	$q_{c,k}$ (MPa)	E (MPa)	φ (degree)
1	[0.0; 0.5]	0.25	9.32	8.22	20.6	35.4
2	[0.5; 1.5]	1.00	11.60	10.52	26.3	36.8
3	[1.5; 2.5]	2.00	14.72	13.77	34.4	38.4
4	[2.5; 3.5]	3.00	15.32	14.67	36.7	38.7
5	[3.5; 4.5]	4.00	17.67	16.45	41.1	39.4
6	[4.5; 6.0]	5.25	19.60	18.33	15.8	40.1
7	[6.0; 8.0]	7.00	21.83	20.58	51.4	40.7

Table 2. Partial factors in EN1997-1 Annex A

Design Approach		γ_G	γ_Q	γ_M	γ_R
DA-1	Comb. 1	1.35	1.5	1.0	1.0
	Comb. 2	1.0	1.3	1.25	1.0
DA-2		1.35	1.5	1.0	1.4
DA-3		1.35	1.5	1.25	1.0

Table 3. Design results based on EC7 DAs.

	DA-1		DA-2	DA-3
	Comb. 1	Comb. 2		
B (m)	1.19	1.57	1.38	1.73
R_d (kN)	2510	2040	2540	2560
V_d (kN)	2510	2040	2530	2560

Table 3 shows the results of the EC7 based design by the different DAs. According to the results, the maximum difference between the results estimated by respective DAs was about 25%.

Furthermore, Figure 2 shows the design results based on NA of several European countries, which are reported by Bond (2010) at the time of the workshop. In this figure, vertical and horizontal axes present the design results of ULS and SLS respectively. Although the concrete contents of the respective NAs are not necessarily clear, the large differences of the results are observed. It is considered that the differences of the design results by different EC7 DAs and NAs based on the same ground information and design conditions indicate reliability difference.

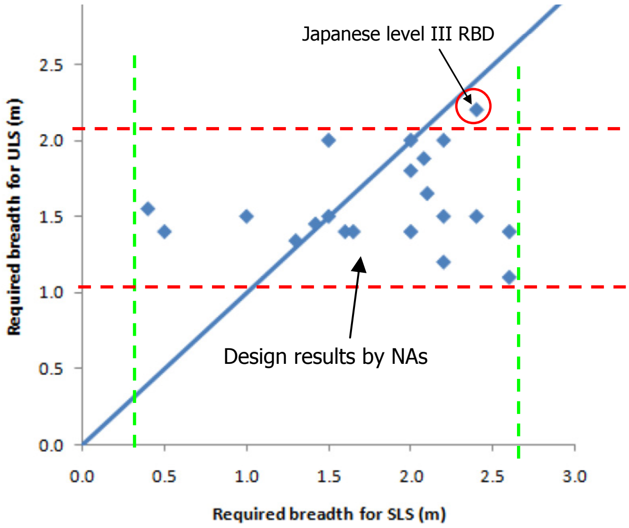

Figure 2. Variation of design results based on NAs

3.3 *A Level III RBD*

The reliability difference of the different design results based on different EC7 DAs and NAs is studied from a level III RBD (Honjo et al 2010). Only the relative reliability level, however, is considered in the study, because the uncertainties in the formulas to derive ϕ' from CPT q_c (EN1997-2 Annex D) and to estimate bearing capacity (EN1997-1 Annex E) are not clear. The different formulas, which uncertainties are analyzed, from EN1997 Annexes' ones are adopted in this design.

Although, designs for both ULS and SLS were carried out in this RBD, due to the limitation of the space, only ULS case is described in this paper.

3.3.1 *Procedure for Level III RBD*

Figure 3 shows the procedure for the level III RBD adopted in this study. This procedure consists of three parts, statistical analysis, geotechnical analysis and reliability analysis. In the statistical analysis, the uncertainties of the formulas to derive geotechnical parameters from subsurface exploration and the inherent vertical and horizontal spatial variations of the geotechnical parameters are quantified. In the geotechnical analysis, a response surface, as an approximate relationship between the structural response and the basic variables is estimated from a series of geotechnical calculations with respect to the vicinity of the limit state (*e.g.* g = R/S =1.0). In the reliability assessment, the reliability is estimated from Monte Carlo Simulation (MCS) based on the uncertainties (obtained from the statistical analysis) and the response surface (obtained from the geotechnical analysis).

Advantage of this procedure is the separation of the geotechnical analysis and the uncertainty analysis. MCS can be carried out without using geotechnical calculation method. Therefore, if the scheme is fitted to include sophisticated geotechnical analysis tools, such as FEM, to level III RBD.

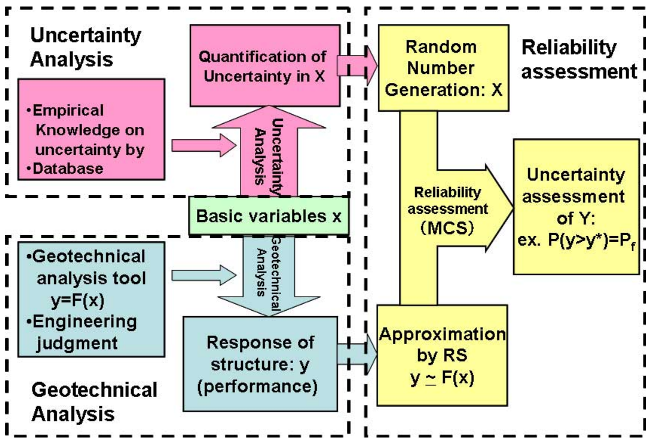

Figure 3. Procedure for a level III RBD

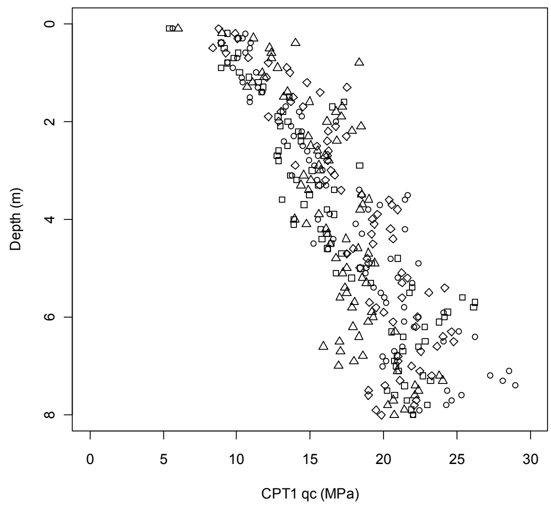

Figure 4. CPT q_c profiles

3.3.2 *Uncertainties*

(1) Inherent spatial variation of CPT q_c

The given q_c values (MPa) at 4 points from the example are plotted in Figure 4. A liner trend model with constant variance along the depth was fitted to this data whose results are presented in Table 4.

Table 4. Result of regression analysis on CPT q_c value.

Variable	Regression coefficient	t-statistics
(Intercept)	10.54	40.9
Depth *z* (m)	1.66	30.1
Residual standard error: 2.28, R^2=0.740, F-statistics: 906.9		

Thus, the trend component of qc (MPa) is obtained for depth z (m):

$$q_c = 10.54 + 1.66 \cdot z \quad (3)$$

The coefficient of determination, R^2, is 0.74, which is fair, and t-values give significantly high values. The residual components of qc are plotted vs. depth in Figure 5. They are found to fit to the normal distribution well with mean value 0 and standard deviation (SD) 2.28 (MPa).

The autocorrelation function is estimated for the vertical direction for each CPT data by the standard moment estimation method, whose results are presented in Figure 6. There are small differences from a CPT to another, however, it is possible to say that autocorrelation distance may lie between 0.4 to0.5m if we fit an exponential type autocorrelation function. Thus we fix it to 0.4m. No correlation for the horizontal direction was found within the data given.

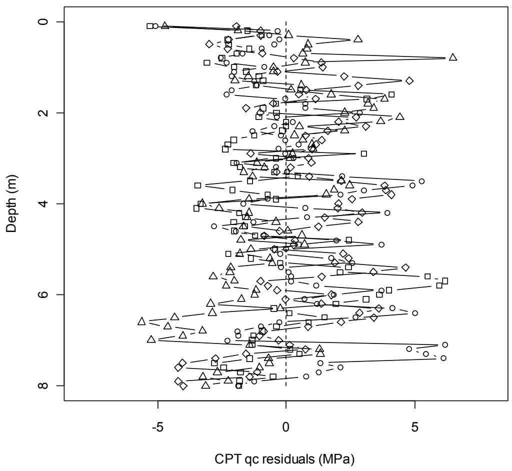

Figure 5. CPT q_c residuals from the trend.

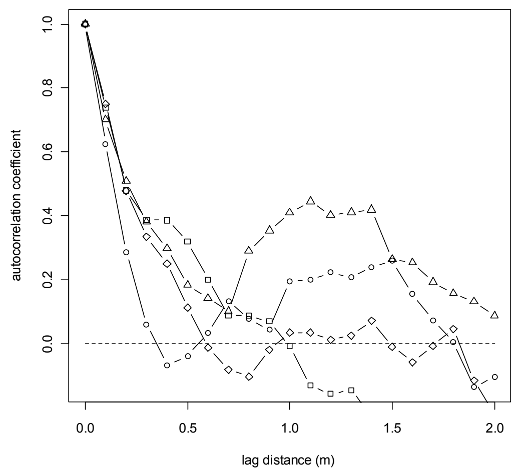

Figure 6. Vertical correlation of the residuals.

Based on these results, the characteristic value of CPT qc at the site is determined as follows;

Mean value: $q_c = 10.54 + 1.66 \cdot z$ (MPa) (4)

Standard deviation: $2.28 \cdot \Lambda_G = 2.28 \times 0.7 = 1.60$ (MPa) (5)

where, Λ_G is estimation variance function (Honjo et al. 2007), that is a function of number of samples (n), spatial averaging distance (L) and autocorrelation distance (θ), which gives the following result;

$$\Lambda_G(n, L, \theta) = \Lambda_G(10, 1.0, 0.4) = \sqrt{0.512} = 0.716 \approx 0.7 \quad (6)$$

(2) Transformation error: Friction angle from CPT

The internal friction angle of the sand layer is estimated from CPT qc values by the correlation, which is described in "Manual on Estimating Soil Properties for Foundation Design (Kulhawy et al. 1990)". In this correlation, the friction angle is related to the normalized cone tip resistance, which is give as equation (7);

$$\phi'_{tc} = 17.6 + 11.1 \cdot \log\left((q_c/q_a)/(\sigma'_{v0}/p_a)^{0.5}\right) \quad (7)$$

where, pa = atmospheric pressure , σ'_{vo} = effective overburden stress. SD of the correlation is estimated to be 2.8 degrees.

Eq. (7) is applied to the given data to convert q_c to ϕ'_{tc} whose results are presented in Figure 7. Due to the effect of the overburden effective stress, the transformed ϕ'_{tc} keeps constant along the depth to 8m except the first 2m where σ'$_{vo}$ is relatively small. It is hard to imagine that the geological origin of the first 2m sand is different from the below layer, thus it is judged that larger ϕ'_{tc} in the first 2m is result of smaller σ'$_{vo}$ that makes the conversion inaccurate. For this reason, ϕ'_{tc} below 2m is statistically treated to obtain the characteristic value of ϕ'_{tc}. The mean and SD of ϕ'_{tc} are estimated to be 42.8degrees and 0.60degerees. since COV of ϕ'_{tc} is much less than 0.01, ϕ'_{tc} is assumed to be a deterministic variable in the further analysis.

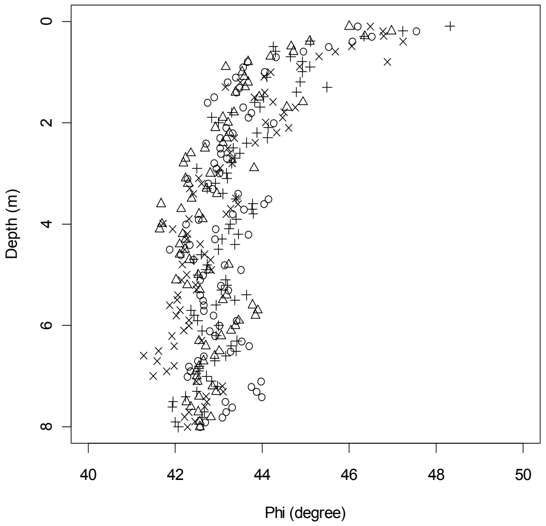

Figure 7. Distribution of converted φ'$_{tc}$ vs. depth

(3) Model error: Evaluation of bearing capacity

The evaluation of bearing capacity, Eq. (8), which is employed in "Specifications of Highway Bridges (JRA 2002)", is adopted in evaluating the bearing capacity of the pad foundation in this design.

$$R_u = A_e\left\{\kappa \cdot q \cdot N_q \cdot S_q + \frac{1}{2} \cdot \gamma_1 \cdot \beta \cdot B_e \cdot N_\gamma \cdot S_\gamma\right\} \qquad (8)$$

$$\kappa = 1 + 0.3 \cdot \frac{D_f'}{B_e} = 1 + 0.3 \cdot \frac{0.8}{B_e} = 1 + \frac{0.24}{B_e},$$

$$q = \gamma_2 \cdot D_f = 20 \cdot 0.8 = 16\ (\mathrm{kN/m^2}),$$

$$N_q = \frac{1+\sin\phi}{1-\sin\phi} \cdot \exp(\pi \cdot \tan\phi),\quad S_q = \left(\frac{q}{q_0}\right)^{\upsilon} = \left(\frac{16}{10}\right)^{-1/3} = 0.86,\quad \gamma_1 = 20\ (\mathrm{kN/m^3}),\quad \beta = 0.6$$

$$N_\gamma = \left(N_q - 1\right) \cdot \tan\left(1.4 \cdot \phi\right),\quad S_\gamma = \left(\frac{B_e}{B_0}\right)^{\mu} = \left(\frac{B_e}{1.0}\right)^{-1/3} = B_e^{-1/3}$$

where, A_e is the effective area of the foundation (= B^2 in this case), B_e is effective width (B_e = B in this case), κ and β are shape factors for N_q and N_γ, q is overburden pressure at the foundation bottom, D'_f is embedded depth, S_q and S_γ are scale factor for N_q and N_γ, B_0 and q_0 are reference width and load respectively. The bias of Eq. (8) has found as 0.894 with SD of 0.257 from the comparison with the calculated results and the plate loading tests (Kohno et al. 2009).

(4) Statistical properties for loads

The statistical properties assumed for the permanent and variable loads are taken from literatures widely accepted in EU (JCSS 2001 and Holicky et al. 2007) as presented in Table 5.

3.3.3 *Reliability analysis and results*

The performance function with employing the bearing capacity formula, Eq. (8), to be used in the reliability analysis is obtained as presented by Eq. (9).

$$M = R_u \cdot \left(B, \phi'_{tc}\right) \cdot \delta_{Ru} - G_k \cdot \delta_{Gk} - Q_k \cdot \delta_{Qk} \qquad (9)$$

where, M is safety margin, R_u is bearing capacity of the foundation, δ_{Ru} is uncertainty in bearing capacity evaluation, G_k is characteristic value of permanent load, Q_k is characteristic value of the variable load, δ_{Gk} is uncertainty in the permanent load, and δ_{Qk} is uncertainty in the variable load.

The properties of basic variables used in the reliability analysis are listed in Table 5.

Table 5. List of basic variables.

Basic variables	Nota-tion	Mean	SD	Distribution type
Spatial variability	ϕ'_{tc}	42.8 (degree)	0	Deterministic variable
Conversion error from q_c	ϕ'_{tc}	42.8 (degree)	2.8 (degree)	Normal
R_u estimation error	δ_{Ru}	0.894	0.257	Lognormal
Permanent action	δ_{Gk}	1.0	0.1	Normal(Note)
Variable action	δ_{Qk}	0.6	0.35x0.6 = 0.21	Gumbel distribution(Note)

(Note) Based on JCSS(2001) and Holicky, M, J. Markova and H. Gulvanessian (2007).

The result of the reliability analysis by Monte Carlo simulation (MCS) with 10,000 runs is presented in Figure 8. According to EN1990 annex B, the target reliability index, β, of 3.8 (i.e. 10^{-4} failure probability assuming a normal distribution for β) is required for an ultimate limit state considering 50 years design working life. Thus, the foundation width of more than 2.2 (m) is necessary.

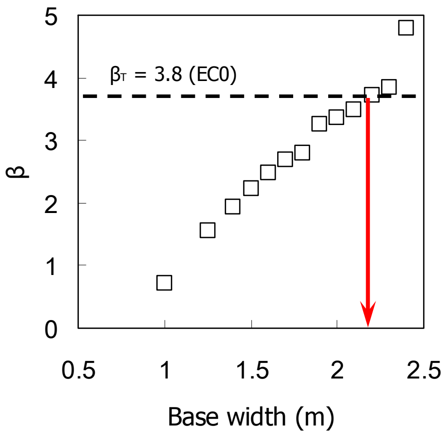

Figure 8. Design results of the RBD

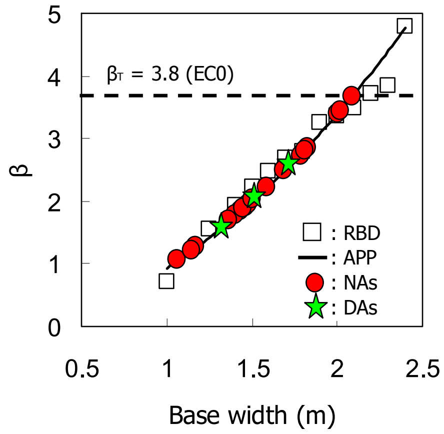

Figure 9. Reliability comparison (ULS)

3.4 *Reliability Difference on EC7 DAs and NAs*

In order to study the reliability differences on the different design results obtained from EC7 DAs and NAs, the results of base width are plotted on an approximate line based on the RBD results as shown in Figure 9. To make reflections on the reliability difference is the objective of this study. However, only relative reliability difference can be considered due to the particular formula to derive φ from CPT q_c and to evaluate the bearing capacity adopted in the RBD. According to the results, it is speculated that the different design results depending on different EC7 DAs and NAs have large relative reliability differences. The differences are as much as about 50% in the DAs' difference, and more than 3 times in the NAs' difference.

4 DISCUSSION

4.1 *Future Issues on EC7*

The authors would like to point out four issues that need to be resolved in EC7 development.

4.1.1 *Different Design Results depending on DAs*

The difference of the design results by the respective DAs under the same design condition, i.e. using the same characteristic values of geotechnical parameters and the same design formula, can be considered as the reliability difference on DAs. However, the ways of determining the characteristic values and design formula are different in various countries, it is not possible to compare the reliability level for each design result. That is to say the error in the transformation from soil investigation results and model error in the design formula are different for different design. If EC7 desires to specify the same reliability level to the different DAs, the RBD similar to the one done in the previous section should be carried out in each case to obtain the reliability level. Otherwise only ways to unify the reliability level would be either unification of DAs to one DA or adjustment of partial factors in the respective DAs so as to obtain the same design result.

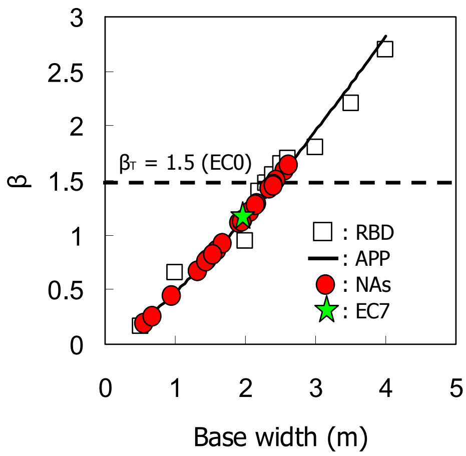

Figure 10. Reliability comparison (SLS)

4.1.2 *Model Error Consideration in Material factor*

According to Eurocode 0 – Basis of structural design –, material factor is to be constituted from uncertainties on both resistance model and material properties. However, it is not clear how EC7 is taking model uncertainty into the partial factors. It goes without saying that the experiences of engineers is important in determination of partial factors in geotechnical design. In spite of this fact, some sort of qualitative consideration concerning the model uncertainty would be necessary.

4.1.3 *Partial Factor depending on subsurface exploration*

Uncertainty of derived geotechnical parameters is different depending on the types of subsurface exploration, e.g. in-situ tests (SPT, CPT and so on) or laboratory tests.

Furthermore, design parameters are derived from the investigation results where transformation error would enter. Hence some quantification on uncertainty on the transformations from subsurface exploration to the geotechnical parameters would be unavoidable.

4.1.4 *Partial Factor for SLS Design*

Variation of the SLS design results obtained from respective NAs is large as shown in Figure 2. The SLS design results plotted on the line based on the SLS RBD are presented in Figure 10. According to the result, the relative reliability difference is extremely large, i.e. more than 10 times by the reliability index. It is speculated that the requirement for reliability level for SLS may be different for different countries. This background need to be disclosed and may be expressed in the form of a partial factor.

4.2 *An Example of Determination of Partial Factors*

Determination of Partial factors based on the target reliability is often employed in the recent development of design codes. The target reliability is determined from reliability level of the existing design practice in this paper, whose procedure is shown in Figure 11. Based on the reliability analysis on the structures designed by current practice, the target reliability level is determined. The partial factors are then determined by trial and error procedure until the structure with the target reliability level is designed. For example, if one set the target β (β_T) to 3.0 based on the fact that the reliability level of the pad footing designed by EC7 DA3 possesses reliability index (β) of about 3.0, the partial factors of the other DAs are calculated as presented in Table 6. Table 7 describes the design results with using determined partial factors. It should be noticed that there are many cases that the load factors are already given, and only the partial factors concerning resistance should be determined. This is also the case for this example, and only the partial factors on resistance are determined.

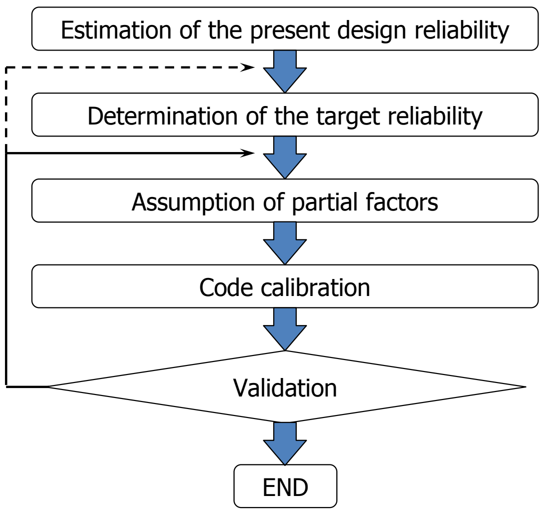

Figure 11. Determination of partial factors

Table 6. An Example of assumption of partial factors

Design Approach		γ_G	γ_Q	γ_M	γ_R
DA-1	Comb. 1	(1.35)	(1.5)	(1.0)	(1.0)
	Comb. 2	1.0	1.3	**1.35**	1.0
DA-2		1.35	1.5	1.0	**2.35**
DA-3		1.35	1.5	1.25	1.0

Table 7. Design results by the assumed partial factors.

	DA-1		DA-2	DA-3
	Comb. 1	Comb. 2		
B (m)	(1.19)	**1.76**	**1.72**	1.73
R_d (kN)	(2560)	2050	2560	2560
V_d (kN)	(2480)	2040	2550	2560

In code calibration, the applicability of the assumed partial factors to structures with different design conditions should be studied. Finally, it should be confirmed that the structures designed by the assumed partial factors preserves the reliability level similar to the target reliability, otherwise the procedure should be repeated until the appropriate partial factors are determined.

4.3 *Target Reliability, Partial Factors and Code Calibration for NAs*

There is a concern that because of the large variation of the results of the design as shown in Figure 2, the foundation design may considerably change in some countries once EC7 fixes a unified reliability level. The authors, however, consider there are some more issues to be investigated before we reach the conclusion above. As discussed in the previous sections, the difference in resulting foundation size may not directly reflect the difference of the reliability level of the respective NAs.

We consider the first step of the flow chart in Figure 11, “Estimation of the present design reliability”, is of vital importance. The transformation from soil investigation results to geotechnical parameters used in design may depend on the type of soil investigation method and soil types. The error involved in this transformation may be affected by many factors including local geological conditions. The inherent spatial variability of the ground may depend on the local geology. Each design formula has different model error. The expected skill for geotechnical engineers may be different for different countries in geotechnical design. After disclosing these factors, we can start to talk about the reliability level of each NA.

Even after these studies, one need to recognize the performance requirements for geotechnical structure may be different from one country to another, e.g. redundancy for the limit state depends on the structure, and/or room for allowable displacement may be different.

5 CONCLUSION

Under the condition that the developments of design codes based on reliability are actively taking place in various parts of the world, this study focused on the differences in the design results by EC7 DAs and NAs, which were reported in ETC10 workshop in Pavia. An example of level III RBD on the examples set by ETC10 are shown together with an example of determination of partial factors, and several important issues concerning the development of DAs and NAs of EC7 are discussed..

Certainly, RBD is not only correct method to evaluate of structural safety. The engineering judgments based on experiences are important to achieve the structural safety in geotechnical design practice. By saying so, it is considered that RBD can serve as an effective tool to solve the issues concerning the reliability level of the geotechnical structures.

REFERENCES

European Technical Committee 10 (ETC10), Design example 2 2010, http://www.eurocode7.com/etc10/index.html

Sorensen, C.S. & Cenor, J.B., Pad foundation with vertical central load on dense sand, 2nd Intl. Workshop on Evaluation of Eurocode 7., Pavia, Italy, http://www.eurocode7.com/etc10/index.html

Orr, T.L.L. 2005, Model solutions for example 1 – Pad foundation with a vertical central load, Proc. of the 1st Intl. Workshop on the Evaluation of Eurocode 7, Dublin Ireland, 77-80

Bond, A. 2010, Introduction to ETC10 design example 2, 2nd Intl. Workshop on Evaluation of Eurocode 7., Pavia, Italy, http://www.eurocode7.com/etc10/index.html

Honjo, Y., Hara, T., Otake, Y. & Kieu Le, T.C. 2010, Reliability based design of examples set by ETC10, Geothchnique, (submitted)

Honjo, Y. & Setiawan, B. 2007, General and local estimation of local average and their application in geotechnical parameter estimations, Georisk, 1(3), 167-176

Kulhawy, F.H. & Mayne, P.W. 1990, Manual on estimating soil properties for foundation design, Report EL-6800, Electric Power Research Inst., Palo Alto, 306 p.

Japan Road Association (JRA) 2002, Specification of highway bridges

Kohno, T., Nakaura, T., Shirato, M. & Nakatani, S. (2009). An evaluation of the reliability of vertically loaded shallow foundations and grouped-pile foundations, Proc. of The Second International Symposium on Geotechnical Risk and Safety (IS Gifu), Gifu, Japan, 177-184

Holicky, M., Markova, J. & Gulvanessian, H. (2007). Code calibration allowing for reliability differentiation and production quality. Applications of Statistics and Probability in Civil Engineering. Kanda, Takada & Furuat (eds)