A Detailed Evaluation of Eurocode and ISO Methodology on Earthquake-Resistant Geotechnical Designs

J. Wang[1] and I. Thusyanthan[2]

[1] *PhD Student, Dept. of Engineering, University of Cambridge, Cambridge, UK*
[2] *University Lecturer, Schofield Centre, Dept. of Engineering, University of Cambridge, Cambridge, UK*
Email: jw455@cam.ac.uk, it206@cam.ac.uk

ABSTRACT :
This paper presents the design concepts of Eurocode 7, Eurocode 8 and ISO 23469. Detailed comparisons are made between Eurocode 8 Part 1 and the ISO code. Conclusions are drawn on their relative merits. A simple strip foundation design example is shown to illustrate the methodology of Eurocode 8. The performance of this design is also evaluated using the PLAXIS Dynamic software package. The results of the dynamic analyses show that the seismic design of simple foundation needs to be performance-based. The Life-Cycle Cost concept mentioned in ISO 23469 is also briefly introduced as a possible performance-based seismic design method for the future.

KEYWORDS:
Eurocode 7, Eurocode 8, ISO 23469, Life-Cycle Cost

1. INTRODUCTION

From 2010, a complete suite of Eurocode will replace national standards to become the common code of practice throughout Europe. As a result, its geotechnical (Eurocode 7) and seismic design (Eurocode 8) sections are becoming standardised tools for European engineers to operate internationally. At the same time, many other countries such as Japan will be implementing ISO standards for design. In particular, the newly published ISO 23469 serves as an explicit counterpart to Eurocode 8, and provides a very different perspective in defining seismic actions on geotechnical structures.

This paper aims to introduce and evaluate the design methodology of Eurocode 7, Eurocode 8 and ISO 23469, and to draw useful conclusions on their relative merits. It also briefly introduces the ISO's Life-Cycle-Costing (LCC) design concept which is currently under development.

2. EUROCODE 7: A BRIEF INTRODUCTION

The most recent version of Eurocode 7 (EC7) was published in 2004, and enjoys the status of a British Standard. It is currently split into two parts:

- **Part 1** (EN 1997-1:2004, or EC7-1), which outlines all the requirements for designing geotechnical structures; And
- **Part 2** (EN 1997-2:2007, or EC7-2), which provides additional design guidelines based on ground investigation and laboratory testing. It serves largely as a pre-requisite stage for EC7-1.

The design philosophy of EC7 is widely welcomed, in that it makes a clear distinction between ultimate limit state (ULS) and serviceability limit state (SLS) requirements. Taking spread foundation design as an example, the following ULS requirements are identified by EC7-1.

- Overall stability;
- Adequate bearing resistance;

- Adequate sliding resistance;
- Adequate structural capacity; And
- No combined failure of ground and structure.

The list on SLS requirements, on the other hand, only outlines the following general aspects:

- No excessive settlement, both immediate and delayed;
- Design against heave, both immediate and delayed; And
- Design for vibrating Loads.

In addition, EC7-1 also adopts a limit-state approach to geotechnical design. For ULS design in particular, it subdivides all relevant requirements into five broad categories:

- **EQU**: *"loss of equilibrium of the structure or the ground"*
- **STR**: *"internal failure or excessive deformation of the structure or structural elements"*
- **GEO**: *"failure or excessive deformation of the ground"*
- **UPL**: *"loss of equilibrium…due to uplift by water pressure (buoyancy) or other vertical actions"*
- **HYD**: *"hydraulic heave, internal erosion and piping in the ground caused by hydraulic gradients"*

Rather than relying upon a large global factor of safety (FoS), EC7-1 uses partial factors to be applied directly to actions (A), material strengths (M), and resistances (R). A unique partial factor set is assigned to each of the five limit states listed above, and ULS safety is verified provided that the total partial-factored action is smaller than or equal to the net partial-factored resistance. For the STR and GEO limit states in particular, the assigned partial factor sets are multi-valued, i.e. include subsets. In order to determine which subset to apply, EC7-1 specifically introduces three new Design Approaches (DAs), and the end design depends heavily on which DA the designer has opted for.

3. EUROCODE 8: AN OVERVIEW

Eurocode 8 (EC8) is a specialised component in the Eurocode family that deals specifically with earthquakes. It covers a vast spectrum from defining seismic actions to detailed structural and geotechnical design aspects. Currently it is split into six parts, and shows a bias towards structural design aspects.

- **EN 1998-1**: (EC8-1) General Rules, Seismic Actions and Rules for Buildings
- **EN 1998-2**: Bridges
- **EN 1998-3**: Assessment and Retrofitting of Buildings
- **EN 1998-4**: Silos, Tanks, and Pipelines
- **EN 1998-5**: (EC8-5) Foundations, Retaining Structures, and Geotechnical aspects
- **EN 1998-6**: Towers, Masts, and Chimneys

In the realm of geotechnical engineering, only EC8-1 and EC8-5 have direct impact on practicing engineers, thus will be the emphasis of this paper.

3.1. EC8-1: Fundamental Requirements

Like EC7, EC8-1 exhibits a similar limit-state approach to seismic design by dividing its fundamental design requirements into two broad categories:

- **No-collapse requirement:**
  "*The structure shall…withstand the design seismic action without local or global collapse, thus retain its structural integrity and a residual load bearing capacity*"; And
- **Damage limitation requirement:**
  "*…to withstand an earthquake without occurrence of damage and limitations of use*"

The first statement clearly corresponds to the ULS case, thus should be associated with "*rare events*" only.

EC8-1 specifies that, unless stated otherwise in the NAD, the applicable earthquake for verification of this criterion should either have a return period of 475 years, or have a 10% probability of exceedance in 50 years. The two criteria are essentially the same from a statistical perspective. The second statement is essentially a different name for SLS, as the emphasis is on "*limitation of use*". For verification of this criterion, smaller earthquakes with a larger probability of occurrence should be chosen, and EC8-1 recommends using either a return period of 95 years or a 10% probability of exceedance in 10 years.

3.2. EC8-1: Methodology

EC8-1 allows five different ways of representing seismic effects on structures:

- Response spectra
- Artificial accelerograms
- Recorded or simulated accelerograms
- Other time-history representations with or without spatial model

However, because of its strong structural bias, EC8-1 only illustrates the *Response Spectra* method in adequate detail, but leaves the other three "*for advanced analysis only*". This method is a simple map-based approach, as the seismic hazard is dependent upon a single parameter, the *Reference Peak Ground Acceleration* (PGA, or a_{gR}). The relevant design process is relatively simple:

Step 1. Determine a_{gR}. The designer is required, first of all, to derive the a_{gR} value based on national seismic hazard zonation maps. This value is usually based upon ULS design considerations, i.e. a return period of 475 years.

Step 2. Determine Building Importance Facrot, γ_I, and, Design Ground Acceleration, a_g. The designer should then assess the desired reliability of the specific structure. For example, public buildings such as schools and hospitals may require a lower probability of occurrence than the reference value, while temporary buildings such as portal frames could tolerate a higher probability as potential losses from earthquakes are low. This Building Importance Factor, γ_I, can thus be calculated for the desired return period T_L or probability of exceedance P_L using Equations (1) and (2) below:

$$\gamma_I = (T_{LR} / T_L)^{-1/k} \tag{1}$$
$$\gamma_I = (P_L / P_{LR})^{-1/k} \tag{2}$$

Step 3. Determine ground type at site. EC8-1 identifies seven distinct ground types to categorize the site-specific earthquake response of the structure:

Type A: rock sites
Type B: very dense sand, gravel or clay
Type C: dense or medium dense sand, gravel or clay
Type D: loose-to-medium cohesionless soil, or soft-to-firm cohesive soil
Type E: surface alluvium underlain by stiffer material
Type S1: soft clay/silt with high PI and high water content
Type S2: liquefiable soils, sensitive clays, and others

This list should, in principle, cover every possible construction site in Europe. It remains dubious, however, in that no distinction amongst gravels, sands and clays is made in any of the ground types put forward by EC8-1.

Step 4. Determine viscous damping ξ of the structure. A structural analysis should then be carried out to determine the aggregate amount of damping the structure can offer. This includes plastic behavior of structural members, presence of plastic hinges, energy absorbance by concrete columns and foundations, and dynamic absorbance via soil-structure interaction (SSI). If advanced analysis is not feasible, a nominal value of ξ = 5% could be adopted.

Type 1 Response spectra

Ground type	S	T_B (s)	T_C (s)	T_D (s)
A	1,0	0,05	0,25	1,2
B	1,35	0,05	0,25	1,2
C	1,5	0,10	0,25	1,2
D	1,8	0,10	0,30	1,2
E	1,6	0,05	0,25	1,2

Type 2 Response spectra

Ground type	S	T_B (s)	T_C (s)	T_D (s)
A	1,0	0,15	0,4	2,0
B	1,2	0,15	0,5	2,0
C	1,15	0,20	0,6	2,0
D	1,35	0,20	0,8	2,0
E	1,4	0,15	0,5	2,0

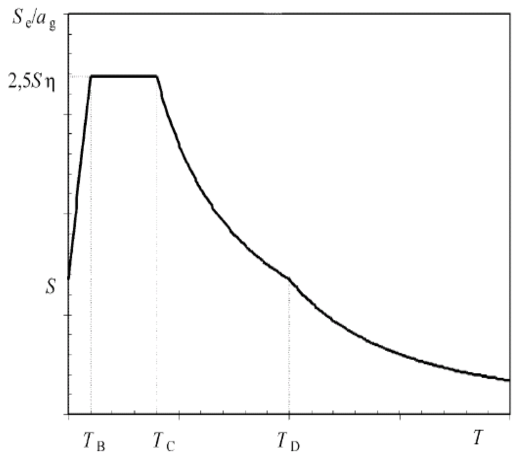

Figure 1: *General shape of Response Spectra*

Step 5. Construct response spectra. Determination of ground types and damping factors lead directly to a set of parameters that determine the shape of the response spectra. If ξ is fixed at 5%, this shape is only dependent upon ground types at site and the surface wave magnitude, M_s, associated with the seismic hazard of the region. EC8-1 suggests two types of response spectra, Type 1 for $M_s > 5.5$ and Type 2 for $M_s \leq 5.5$, and either should be used as dynamic inputs from earthquake actions. *Figures 1 and 2* are simple illustrations of how different ground types and the value of M_s can influence the shape of EC8-1 response spectra for the horizontal component of seismic actions. A number of other parameters, such as peak horizontal acceleration at surface and design ground displacement can also be determined analytically at this stage, using formulae specified in EC8-1.

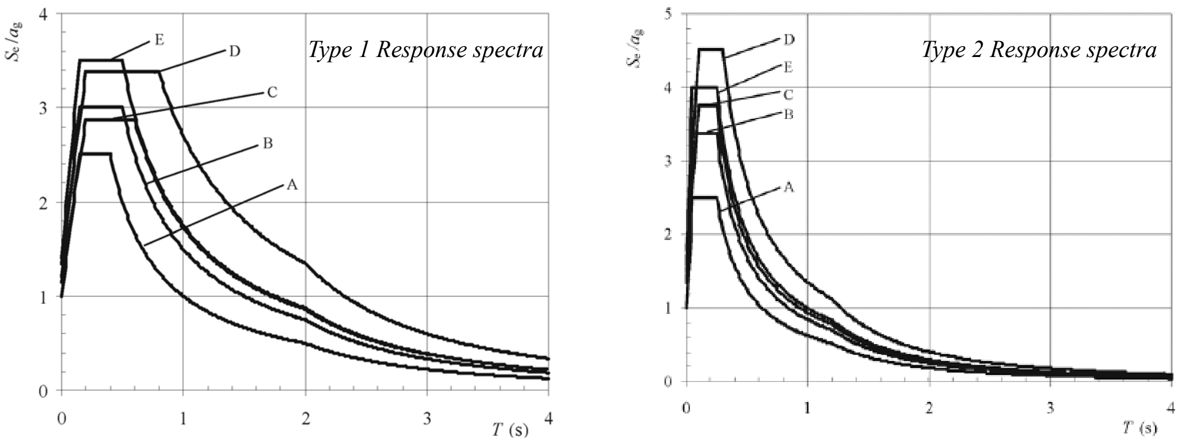

Figure 2: *Recommended elastic Response Spectra for Ground Types A to E (5% damping)*

3.3. EC8-5: An Overview and Evaluation

EC8-5 is a single document that covers all geotechnical seismic design aspects. It offers requirements on ground properties, choice of site, foundation systems, soil-structure interaction, and earth-retaining structures. The code itself is surprisingly short, just shy of 50 pages. It also opens up scope for improvement in many areas.

First of all, EC8-5 shows no explicit embodiment of EC8-1's Damage Limitation State concept, while bases its criteria almost purely upon permissible ULS displacements. Secondly, although EC8-5 is largely a subsidiary to EC7, their design methodologies do not coincide. For example, EC8-5 clearly states that its provisions are "*in addition to…EC7-1*", but does not explicitly employ any of the three Design Approaches when assessing STR and GEO limit-states. Another question is how the "design normal force" (N_{Ed}) or "design friction resistance"

(F_{Rd}) in EC8-5 should be related to V_d and R_d in EC7-1, and what partial factor sets should be applied to them. Issues of this kind are making EC8-5 almost incompatible with EC7-1, and are confusing designers widely. Last but not least, EC8-5 also exhibits a strong structural bias, and does not explicitly address the probabilistic nature of soil properties and safety during the earthquake. For example, its "*normative*" (i.e. obligatory) Annex B employs a highly simplified chart to analyse liquefaction potential based on SPT blow-count alone. This approach is rather questionable, in that SPT data is a poor indication of the relative density of sands to their critical state values. The British Standards Institution, BSI, is yet to publish the UK NAD for EC8-1 and EC8-5. Proposals have also been put forward for a thorough review of EC8-5 to make it more suitable for geotechnical applications.

3.4. EC8-5 on Strip Foundation Design: A Worked Example

EC8-5 provides a relatively detailed section on foundation systems. However, relevant guidance on serviceability remains implicit. For example, according to its Section 5 and Annex F, seismic bearing "safety" of a strip footing can be verified using the following mega-equation:

$$\frac{(1-e\overline{F})^{c_T}(\beta\overline{V})^{c_T}}{\overline{N}^a\left[\left(1-m\overline{F}^k\right)^{k'}-\overline{N}\right]^b}+\frac{(1-f\overline{F})^{c'_M}(\gamma\overline{M})^{c_M}}{\overline{N}^c\left[\left(1-m\overline{F}^k\right)^{k'}-\overline{N}\right]^d}-1\le 0 \qquad (3)$$

Where $\overline{N}=(\gamma_{Rd}N_{Ed})/N_{\max}$, $\overline{V}=(\gamma_{Rd}V_{Ed})/N_{\max}$, and $\overline{M}=(\gamma_{Rd}M_{Ed})/(BN_{\max})$ .In this equation, $\overline{N}$, $\overline{V}$ and $\overline{M}$ are the non-dimensional parameters for vertical, horizontal and bending moment loading respectively during the seismic event. N_{max} is the ultimate bearing capacity per unit length along the foundation; B is the foundation width; $\overline{F}$ is the dimensionless soil inertia force; and γ_{Rd} is the soil model partial factor. The seismic design action force per unit length, N_{ed}, should combine static loading forces with the dynamic inertia forces due to displacements of the super-structure. Normally N_{ed} should be determined from a separate seismic structural loading analysis.

As a simple design example, it can be verified that a 4.08 m wide strip footing can "safely" sustain a vertical dynamic loading of N_{ed} = 240 kNm^{-1} combined with a horizontal V_{ed} = 12.3 kNm^{-1} according to EC8-5. It is also obvious that safety will be governed by bearing in this scenario ($N_{ed}>>V_{ed}$). The relavant soil parameters are: saturated unit weight γ_{sat} = 18 kNm^{-3}; undrained shear srength s_u = 30 kPa; and soil category is Type E by EC8-1. All additional recommended parameter values in EC8-1 and EC8-5 are listed in *Table 1*.

Table 1: *Seismic parameters based on EC8-1 and EC8-5*
Soil Type: Purely Cohesive Soil, Model Partial Factor: γ_{Rd} = 1.00 for non-sensitive clays

EC8-1 Parameters	Partial Factors (from EC8-5)	EC8-5 Parameters
a_{gR} = 0.5 g γ_I = 1.1; M_s = 6.0 Type E Ground γ_I = 1.1; S = 1.4 T_B = 0.15; T_C = 0.5 T_D = 2.0	$\gamma_M = \gamma_{cu}$ = 1.4	a = 0.7; b = 1.29 c = 2.14; d = 1.81 e = 0.21; f = 0.44 m = 0.21; k = 1.22 k' = 1.0; c_T = 2.0 c_M = 2.0; c'_M = 1.0 β = 2.57; γ = 1.85

The ultimate bearing capacity, N_{max}, per unit length of a strip foundation can be derived using Equation (4) below from Annex F of EC8-5:

$$N_{\max}=(\pi+2)\frac{c_u}{\gamma_M}B=(3.14+2)\times\frac{30}{1.4}\times 4.08=449.5\ kNm^{-1} \qquad (4)$$

The total bearing capacity, $N_{max,tot}$, for 1 m along the strip is then: $N_{max,\ tot}$ = 449.5 × 1 = 449.5 kN

The values of $\overline{N}$ and $\overline{V}$ can now be easily determined using Equations (5) and (6) from the same Annex.

$$\overline{N} = \frac{\gamma_{Rd} N_{Ed}}{N_{\max,tot}} = \frac{1.00 \times 240}{449.5} = 0.534, \quad (0 < \overline{N} < 1, \text{ thus OK!}) \tag{5}$$

$$\overline{V} = \frac{\gamma_{Rd} V_{Ed}}{N_{\max,tot}} = \frac{1.00 \times 12.3}{449.5} = 0.0273, \quad (\left|\overline{V}\right| < 1, \text{ thus OK!}) \tag{6}$$

The dimensionless soil inertia force, $\overline{F}$, for a "*purely cohesive*" soil is given by:

$$\overline{F} = \frac{\rho \cdot \gamma_I \cdot a_{gR} \cdot S \cdot B}{c_u} = \frac{1837 \times 1.1 \times 0.5 \times 9.81 \times 1.4 \times 4.08}{30000} = 1.885 \tag{7}$$

Putting these numbers altogether, the LHS of Equation (3) that governs seismic bearing "*safety*" becomes:

$$LHS = \frac{(1-0.21\times1.885)^{2.0} \times (2.57\times0.0273)^{2.0}}{0.534^{0.7}\left[\left(1-0.21\times1.885^{1.22}\right)^{1.0} - 0.534\right]^{1.29}} + 0 - 1 = -0.018 < 0 \tag{8}$$

This value is very close to boundary. It may thus be concluded that 4.08 m is the minimum dimension that could make the design "safe" to EC8-5 standards. However, Equation (8) fails to address critical design issues such as:

- Maximum allowable displacement and tilt;
- Measure of reliability, e.g. equivalent overall factor of safety (OFS); And
- Maximum allowable damage and cost of repair, and the evaluation method of such.

In addition, analytical "cut-off" points offered by Equation (8) are, in general, over-conservative. As a simple illustration, numerical simulations were conducted for four design widths, 3.96 m (97% of critical), 4.08 m, 4.20 m (103%), and 4.49 m (110%), using the Plaxis2D™ Dynamic™ software package. The earthquake applied was a horizontal sinusoidal shear wave with a maximum acceleration of 0.5g. The foundation was assumed rigid, and restricted to move and rock in a plane-strain fashion. The performance of each is summarised in *Table 2*.

Table 7: *Summary of Plaxis results for 4 foundation designs using Mohr-Coulomb Soil Model,* $\varphi' = 30°, c' = 2$ *kPa,* $E = 22{,}000$ *kPa,* $k = 1 \times 10^{-8}$ ms^{-1}.

Design Width (m)	LHS Value of Equation (3)	Max. Vertical Displ. (mm)	Max. Hori. Displ. (mm)
3.96	∞	96	46
4.08	- 0.018	92	44
4.20	- 0.700	89	41
4.49	- 0.903	75	31

Although these results are of indicative nature, it is clear that a mere 3% reduction from the critical foundation width would push the LHS value of Equation (8) from –0.018 to infinity. The associated maximum vertical and horizontal displacement, on the other hand, only increases by 4 mm (4.3%) and 2 mm (4.5%) respectively. On the other hand, a tiny increase in design width from the cut-off would put the LHS value onto the flat region, but offers little corresponding improvements in seismic performance. It should also be noted that Equation (3) is, in principle, applicable to strip footings only. This makes it rather useless for practicing engineers. As a result, many designers have attempted to use the same equation for rectangular pads, which is quite worrying.

4. ISO 23469: AN OVERVIEW

The newly published ISO 23469:2005, *Bases for design of structures – Seismic actions for designing* *geotechnical works*, provides guidelines for defining seismic actions on geotechnical structures. It is suitable for a wide range of applications from buried structures to landfills. Like EC8-1, ISO 23469 also divides performance objectives into two broad categories:

- **Serviceability**
  - Minor impact to social and industrial activities;
  - Structure remain functional and operational, or economically recoverable;
  - For earthquakes with "reasonable probability of occurrence"; And
- **Safety**
  - Minimise human casualty and damage to property;
  - Important facilities remain operational, and essential geotechnical works shall not collapse;
  - Associated with "rare events" only.

However, the ISO code places a great emphasis on functionality and damage-minimisation after the earthquake. The design philosophy of ISO 23469 is to provide a set of performance-based design guidelines, rather than to rely upon displacement parameters alone like EC8-1. This is very appropriate for large geotechnical projects such as highway embankments and earth dams whose serviceability are of primary concern.

4.1. ISO 23469: Methodology and Comparison with EC8-1

Unlike the EC8-1 approach, the ISO code splits the design process into two broad steps, "*characterising seismic action*" and "*specifying seismic action*". During the first step, the designer is required to go through a checklist type of procedure to correctly identify the design aspects to be considered. The designer should then choose one out of four broad methods of analysis based on these results, and specify the actual design seismic actions during the second step. This is very different from the EC8-1 approach, where the response-spectrum method (a simplified equivalent static approach) is strongly preferred even for structures such as dams and slopes.

Another notable feature of the ISO methodology is the absence of seismic hazard zonation maps which is the basis of EC8-1. ISO 23469 adopts a much more informed approach towards evaluating seismic hazards, in that the designer must "*identify earthquake sources around the site of interest*" by himself. Such sources include both "*areal sources*" and "*fault sources*". Both are characterised by specific known faults around the site of interest. Because of this complication, the seismic hazard in ISO 23469 can no longer be specified via a single parameter (like a_{gR} in EC8-1). If probabilistic analysis is adopted, hazard curves have to be developed for every possible seismic source with different recurrence rates and magnitudes. If deterministic analysis is used, i.e. seismic hazard represented by individual earthquake scenarios, the designer must incorporate the attenuated earthquake magnitude, fault location and dimension, and the source mechanism into the chosen scenario. Therefore, regardless of the method chosen, the first step is always to identify the earthquake sources around the site of interest. Compared with the zonation-map based approach of EC8-1, the ISO code requires a more in-depth understanding of seismic activities from the designer, as seismic hazards must be determined from scratch.

ISO 23469 should also be praised for its greater flexibility over EC8-1. For example, the ISO code does not prescribe any specific "ground types" to restrict the designer, but considers the overall influence of site parameters on the seismic motion. These parameters include shear wave propagation, frequency filtering and amplification, liquefaction analysis, spatial variation of earthquake ground motion, probabilistic soil properties, and so on. An "*informative*" Annex is provided for each of the above, acting as a checklist for designers.

4.2. A Brief Look at LCC Analysis

Conventionally, seismic-resistant geotechnical design has been governed by safety, which is mostly acceptable for countries with low-medium seismic activities. But for highly seismic regions such as Japan, this approach is becoming more and more problematic, as the ever increasing intensity of design earthquakes is making it very expensive to maintain a certain factor of safety above unity. To cope with this problem, ISO 23469 explicitly mentions, in its *Annex D*, the LCC concept as a distinct possible future direction. This concept exemplifies the philosophy of performance-based seismic design. The LCC can be defined as:

$$LCC = C_i + C_m + \Sigma P_k C_{e,k} \tag{9}$$

Where C_i represents the initial construction cost, C_m the maintenance cost, P_k the probability of occurrence of the earthquake event, and $C_{e,k}$ the associated damage cost. The goal is then to determine an initial design that would minimise the total LCC (*Figure 3*).

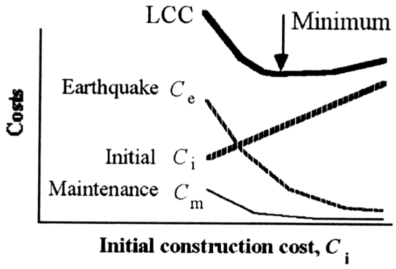

Figure 3: *Conceptual Illustration of Minimization of life cycle cost (LCC), after I. Towhata et al 2008*

However, there are still problems in the application of LCC calculations in geotechnical projects. Firstly, the design life of a geotechnical structure cannot be defined clearly as soil does not deteriorate in time. Secondly, the relationship between the quality of initial construction and the amount of maintenance work is unclear. Last but not least, the indirect seismic costs such as environmental and social-economical impacts are next to impossible to evaluate. Therefore, the LCC approach to seismic geotechnical design is likely to continue its case-by-case attempt in the near future, but is definitely a sound future direction. It should only be properly codified into ISO after these problems have successfully been resolved from design practice and experience.

5. CONCLUSIONS

EC7-1 adopts a limit-state approach to geotechnical designs, and emphasize on analytical methods based on partial factors, equations, and charts. EC8-1 specifies two broad requirements for seismic design: the "no collapse" requirement and the "damage limitation" requirement. It shows a bias for structural applications, and adopts an approach based on seismic hazard zonation maps and the response spectra for specification of seismic hazards. EC8-5 shows a similar bias, and could be improved in many areas such as compatibility with EC7-1, liquefaction assessment, soil type determination, and etc. Results from numerical simulations revealed the sensitivity of the design equation for seismic bearing capacity of strip footings specified in EC8-5. They also revealed that serviceability is a vital criterion in assessing seismic performance of geotechnical designs. Compared with EC8, ISO 23469 offers greater flexibility over the choice of design method, and adopts a more in-depth approach towards specifying earthquake hazards on structures. It provides a good, if not better, alternative to Eurocode 8 for geotechnical applications. The ISO code also explicitly mentions LCC as a possible future direction, which can be a sound performance-based design method in the future.

REFERENCES

Simpson, B and Driscoll, R. (1998). Eurocode 7: A Commentary, IHS BRE Press, Watford, UK.

Fardis, M.N. et al. (2005). Designers' Guide to EN 1998-1 and EN 1998-5. Eurocode 8: Design of Structures for Earthquake Resistance. General rules, seismic actions, design rules for buildings, foundations and retaining structures. Eurocode Expert, ICE and Thomas Telford, UK.

Wang, J. and Thusyanthan, I. (2008) Evaluating Foundation Design Concepts of Eurocode 7 & 8, Proceedings of the 2nd BGA International Conference – ICOF 2008, IHS BRE Press, UK.