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Technical note

Evaluation of codified elastic design spectrum models for regions of low-to-moderate seismicity

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ABSTRACT

Design spectrum (DS) model is typically specified in a seismic code of practice for structural design. In a region of low-to-moderate seismicity where seismic code does not exist, a DS model in a well established code of practice is usually adopted, while the suitability of such model has seldom been evaluated. In this article, the elastic DS models for reference (rock) site stipulated in six major codes of practice (AS1170.4–2007, EN1998-1:2004, GB50011–2010, IBC–2012, NBCC–2010 and NZS1170.5:2004) have been compared and scrutinized. Three cities of low-to-moderate seismicity, namely, Melbourne (Australia), Hong Kong (China) and Karlsruhe (Germany), have been selected for illustrative purposes. Particular emphasis has been put on the parameterization scheme for DS model. It is found that huge discrepancies (over 100%) exist among the models, especially at the long period range, due to differences in spectral shapes and the recommended corner periods, which would lead to undesirable effects on the use of the displacement-based seismic design approach. It is urged that the values of corner periods should be determined specifically and cautiously based on the regional seismicity pattern and local geological conditions.

1. Motivation of the study

In recent years, there have been extensive infrastructure and property developments in many emerging economies around the world, particularly in Asia and the Middle East. Many of these countries are located in regions of low-to-moderate seismicity, and seismic design was typically not a design requirement. However, there is an increasing concern about the potential earthquake threats in those regions, as earthquakes of moderate magnitude occur in unexpected locations and along unknown faults, even though they are located well away from any tectonic plate margins.

Some of these countries are currently developing their own seismic requirements or codes for the first time. Due to the lack of knowledge and experience, a design spectrum (DS) model in a well established code of practice is typically adopted in those regions, based on various inappropriate or non-scientific considerations such as geographical proximity, historical and political relationships, and so forth. However, the suitability of such model has seldom been scrutinized on a scientific and regional-specific basis.

In this article, the parameterization schemes adopted for the horizontal elastic DS models for reference (rock) site stipulated in six major codes of practice will be evaluated and compared in the context of low-to-moderate-seismicity regions using three cities on different continents as a reference case study. The six major codes of practice included in this study are: (1) Australian Standard (AS 1170.4–2007) [1], (2) Eurocode 8 (EN 1998-1:2004) [2], (3) Chinese Code for Seismic Design of Buildings (GB 50011–2010) [3], (4) International Building Code (IBC–2012) [4], (5) National Building Code of Canada (NBCC–2010) [5], and (6) New Zealand Standard (NZS 1170.5:2004) [6].

Near-fault effects and the effects of vertical ground motions are not considered in this study, as these two aspects are considered less important in regions of low-to-moderate seismicity. The site factors or coefficients which are used for taking into account the modification effects from the near-surface sediments would definitely affect both the spectral amplitudes and the spectral shape, but the discussions of the site classification scheme and the values of site factors are beyond the scope of this paper.

2. Parameterization scheme for codified DS models

2.1. Introduction of DS model

The purpose of a DS model is for the analysis and design of structure. DS should ideally be representative of the earthquake ground motion characteristics that are anticipated at the site of

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interest. As the shape of a recorded response spectrum is highly irregular, with undesirable fluctuations in spectral values against small changes in structural period T, a set of smooth curves and/or straight lines is used for constructing the DS. In order to achieve a consistent format of the DS across the whole country or region to where the code is applied, parameterization scheme is required, which can differ significantly from one code to another even though the tectonic and geological conditions of the two regions are similar. There are two types of parameters that determine the DS. The first type is used for scaling the hazard level, while the second type controls the spectral shape including the corner periods as well as the equation forms of the idealized curves/lines.

Development of DS can be more complicated for sites that are subjected to seismic hazards from a variety of sources, e.g. short-period (high-frequency) motions from small earthquakes on nearby sources and long-period (low-frequency) motions from moderate to large earthquakes on distant sources, between which the spectral shape could be highly distinct. This situation is commonly encountered in regions of low-to-moderate seismicity, where earthquake sources are more diffused and not well defined. This problem could be solved by computing a uniform hazard spectrum (UHS), of which each spectral ordinate is obtained by probabilistic seismic hazard assessment (PSHA), with proper considerations of all potential earthquake sources. The UHS obtained by such approach has a uniform (or constant) probability of exceedance at all structural periods. In other words, the use of UHS as the DS would (ideally) produce structural designs with the same probability of failure. Hence, UHS will be used as a benchmark for comparison in this study.

2.2. Scaling parameters

The seismic hazard level of the site should be reflected by certain spectral parameters as obtained in PSHA. In an acceleration DS format, peak ground acceleration (PGA) and/or response spectral acceleration (RSA) at certain value(s) of structural period (T) are/is commonly selected as the scaling parameter(s) or the anchoring point(s). Each region, typically with size of a city, is assigned with a set of parameters for the construction of DS according to the stipulated code of practice. Each parameter, e.g. PGA, is specified in the format of a zoning map, or other formats, such as tables or an appendix, or both. Table 1 summarizes the scaling parameters of each codified DS model.

Among the six major codes of practice, PGA is chosen as the scaling parameter for constructing DS in five of them, namely, AS1170.4 (abbreviated as AS hereafter), EN 1998-1:2004 (abbreviated as EC hereafter), GB 50011–2010 (abbreviated as GB hereafter), NBCC–2010 (abbreviated as NBCC hereafter) and NZS 1170.5:2004 (abbreviated as NZS hereafter). Using Chinese code (which is relatively more difficult to be accessed by international readers) as an illustration: the whole country of China is divided into 40,000 grids, and each of those is specified by a value of design PGA, ranging from 0.05 g to 0.40 g, with a probability of exceedance of 10% in 50 years.

In the International Building Code (abbreviated as IBC hereafter), RSA values at natural period of 0.2 s and 1.0 s are chosen as the scaling parameters for constructing DS, which can roughly mimic a UHS. It is noted that RSA at 0.2 s is typically representative of the maximum value of RSA (i.e. RSA_{max}). It is noted that in NBCC, apart from the value of PGA, RSA values at periods of 0.2, 0.5, 1.0 and 2.0 s are used for constructing DS (of the reference site condition) which closely matches the shape of the UHS. In fact, this is considered more appropriate to scale the DS using more than one parameters [7].

2.3. Equation forms

The scaling parameters in Section 2.2 have a determining influence on the level of seismic loading, especially for structural systems with short natural period. However, there are other spectral parameters, including corner periods as well as the equation forms of the idealized curves/lines, which could substantially control the spectral values at the intermediate to long period range, but their significance is usually undermined in the RSA format.

A constant–acceleration range, a constant–velocity range (RSA being proportional to $1/T$) and a constant–displacement range (RSA being proportional to $1/T^2$) have been recommended in the Newmark–Hall DS format [11], which has strongly influenced the spectral shape of DS models in various codes of practice. The major features of the equation forms adopted in various codes are summarized in Table 2. A constant–acceleration range is specified

Table 1
Summary of the key features controlling DS models in various codes of practice, with reference to the design PGA (g) values (return period of 475 years) across the principal applicable region.

Code	Scaling parameter(s)	Corner periods	PGA (g) values across the country/region
AS	PGA	One set	0.03 (very low) to 0.22 (moderate) [1]
NZS	PGA	One set	0.13 (moderate) to 0.6 (very high) [6]
EC	PGA	Two sets	~0.01 (very low) to 0.4 (high) [8]
GB	PGA	Three sets	0.05 (low) to 0.4 (high) [3]
IBC	RSA (0.2, 1.0 s)	Location-specific	~0.01 (very low) to ~1.0 (very high) [9]
NBCC	PGA, RSA (0.2, 0.5, 1.0, 2.0 s)	Location-specific	0.021 (very low) to 0.59 (very high) [10]

Table 2
Summary of the equation forms for different period ranges in various codes of practice.

Code	$T \leq T_1$	$T_1 \leq T \leq T_2$	$T \geq T_2$
AS	Constant–acceleration	Constant–velocity ($1/T$)	Constant–displacement ($1/T^2$)
EC	Constant–acceleration	Constant–velocity ($1/T$)	Constant–displacement ($1/T^2$)
IBC	Constant–acceleration	Constant–velocity ($1/T$)	ASCE/SEI Standard 7–10 [12]: Constant–displacement ($T_2 \geq 4.0$ s)
GB	Constant–acceleration	$1/T^{0.9}$	$(0.2)^{0.9}$–$0.02(T-5T_1)$
NZS	Constant–acceleration	$1/T^{0.75}$ (< 1.5 s) & $1/T$ (1.5–3.0 s)	Constant–displacement ($1/T^2$)
NBCC	UHS (no standard equation form)		

for the DS models in five major codes, with an exception of NBCC which has adopted UHS as the reference DS model.

Between the first corner period (T_1) and the second corner period (T_2), a constant-velocity range is specified in AS, EC and IBC, while a different functional form of $1/T^{0.9}$ is specified in GB for more conservative loading estimates. In NZS, the range of $T_1 \le T \le T_2$ is further divided into two portions, with a conservative function of $1/T^{0.75}$ up to 1.5 s, and then followed by a constant velocity range up to 3.0 s.

Beyond the second corner period (T_2), a constant–displacement range is specified in AS, EC and NZS. Although IBC neither specify a second corner period nor a different equation form, the ASCE/SEI Standard 7–10: Minimum Design Loads for Buildings and Other Structures [12] specifies another corner period (parameterized as T_L in [12]) (≥ 4.0 s), beyond which the values of *RSA* follow a decreasing curve with a function of $1/T^2$ (i.e. constant–displacement). In GB, a decreasing line with a linear function is adopted between $T=5T_1$ (can be taken as T_2) and $T=6.0$ s, of which the rate of decrease (in RSA) is even slower than the function of $1/T^{0.9}$. Such linear function does not match with a typical UHS nor a response spectrum of any earthquake scenario, and it is different from the equation form being adopted internationally. This can be treated as a minimum lateral force requirement for long-period structures (e.g. high-rise buildings), but such equation form would lead to abnormal increase in the displacement demand in the long period range (to be discussed in Section 3).

2.4. Corner periods

Even the equation forms are the same in two codes, the use of different corner period values would lead to substantial differences in the loading demand. For instance, the use of 0.4 s (EC1) for T_1, instead of 0.3 s (AS), would lead to 33% increase in the demand for structures with natural periods exceeding 0.4 s (i.e. buildings with around five or more stories). Hence, such values should be decided according to the spatial distribution of seismicity and the design earthquake scenarios that are representative of the considered level of probability of exceedance. This has to be done on a city-specific or regional-specific basis. Citing EC as an example, EC has recommended two types of DS: one for the higher seismicity areas (Type 1, annotated as EC1) and the other for the less active areas (Type 2, annotated as EC2). The spectral shapes are mimicking the spectral shapes of large ($M=7\sim7.5$) and small ($M=5.5$) magnitude events occurring at a site-source distance of 10 km, which would in effect result in different sets of corner periods. However, suitable values of corner periods could be investigated and specified in the National Annex of a country, and it is not necessary to stick to the use of either EC1 or EC2.

If a DS model is developed for a large region or country, where the level and pattern of seismicity vary substantially across the region/country, different sets of corner periods should ideally be used for different locations so as to achieve an appropriate spectral shape for the DS model. Table 1 summarizes the relevant features in the six codes with reference to the respective level of seismic hazard across the principal applicable region. Only one set of corner periods (for rock sites) is adopted in AS and NZS, respectively, which can be justified by the relatively more confined levels of seismic hazard across each of the two countries. EC and GB recommend two and three sets of corner periods, respectively, which could suit the wider ranges of seismic hazard level across Europe and China. Due to the very wide range of PGA values in North America, both IBC and NBCC specify more than one anchoring spectral points, which would allow for the construction of location-specific DS model with a spectral shape that can mimic a UHS as much as possible.

3. Comparison of codified DS models

The UHS for rock sites in three cities of low-to-moderate seismicity, namely, Melbourne (Australia) [13], Hong Kong (China) [14,15] and Karlsruhe (Germany) [16], have been selected for illustrative purposes. The UHS were obtained through PSHA for return period (RP) of 475 years or 2475 years. The spectral values have all been normalized to RSA_{max}, as shown in Fig. 1, such that only the spectral shape is compared. It is found that the four normalized UHS have rather similar spectral shape. As the spectral values for Melbourne and Karlsruhe are available up to 1.0 s only, it is reasonable to use the UHS for Hong Kong (available up to 5.0 s) in the following comparison and analysis.

Normalized DS for rock sites have been constructed in the RSA format based on the five codes of practice. Fig. 2(a) and (b) shows the DS for the short-period range up to 1 s and the long-period range between 1 and 4 s respectively. At the short-period range, where the RSA_{max} plateau is located, the DS should ideally be constructed as close as possible to the UHS. When the spectral values at 0.5 s of various DS are normalized to that of the UHS, the ratios range between 0.94 (IBC) and 1.76 (EC1), as shown in Fig. 2(d) and tabulated in Table 3. Such deviation can be attributed to the differences in the values of the first corner period T_1 that range from 0.21 s (IBC) to 0.4 s (EC1). It is observed from Fig. 2(a) that EC1 and NZS models poorly mimic the shape of the UHS, as both models are designed for regions of higher seismicity, while NZS gives larger spectral value at 0.5 s as it follows a function of $1/T^{0.75}$ between T_1 (0.3 s) and 1.5 s. The value of T_1 in IBC is controlled by the spectral values at both short period ($T=0.2$ s) and long period ($T=1.0$ s), which explains the closer match with the UHS. The value of T_1 in GB varies with the seismicity pattern of the location, a value of 0.25 s is recommended for regions of lower seismicity.

Such trend continues to the long-period range as shown in Fig. 2(b). For the above-mentioned reasons, IBC matches the UHS well while NZS gives exceptionally large values. The DS of AS beyond 2 s gives very close values to the UHS, partly because a smaller second corner period T_2 of 1.5 s has been introduced, in contrast to 2.0 s in EC1 and 3.0 s in NZS. Although the DS of GB performs very well at the short-period range (up to around 0.8 s), the long-period range performs poorly as the decreasing curve between $T_1 < T < 5T_1$ has an exponent of 0.9. The linear function beyond $5T_1$ (1.25 s in this case) leads to a much slower decreasing rate, which results in an unreasonable spectral shape at the long-period range, especially in the response spectral displacement (*RSD*) format, as shown in Fig. 2(c).

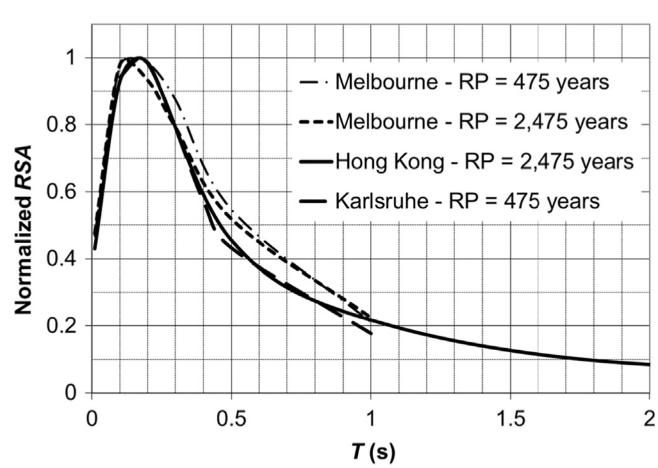

Fig. 1. The normalized UHS for rock sites in Melbourne (Australia), Hong Kong (China) and Karlsruhe (Germany) with return period (RP) of 475 years or 2475 years.

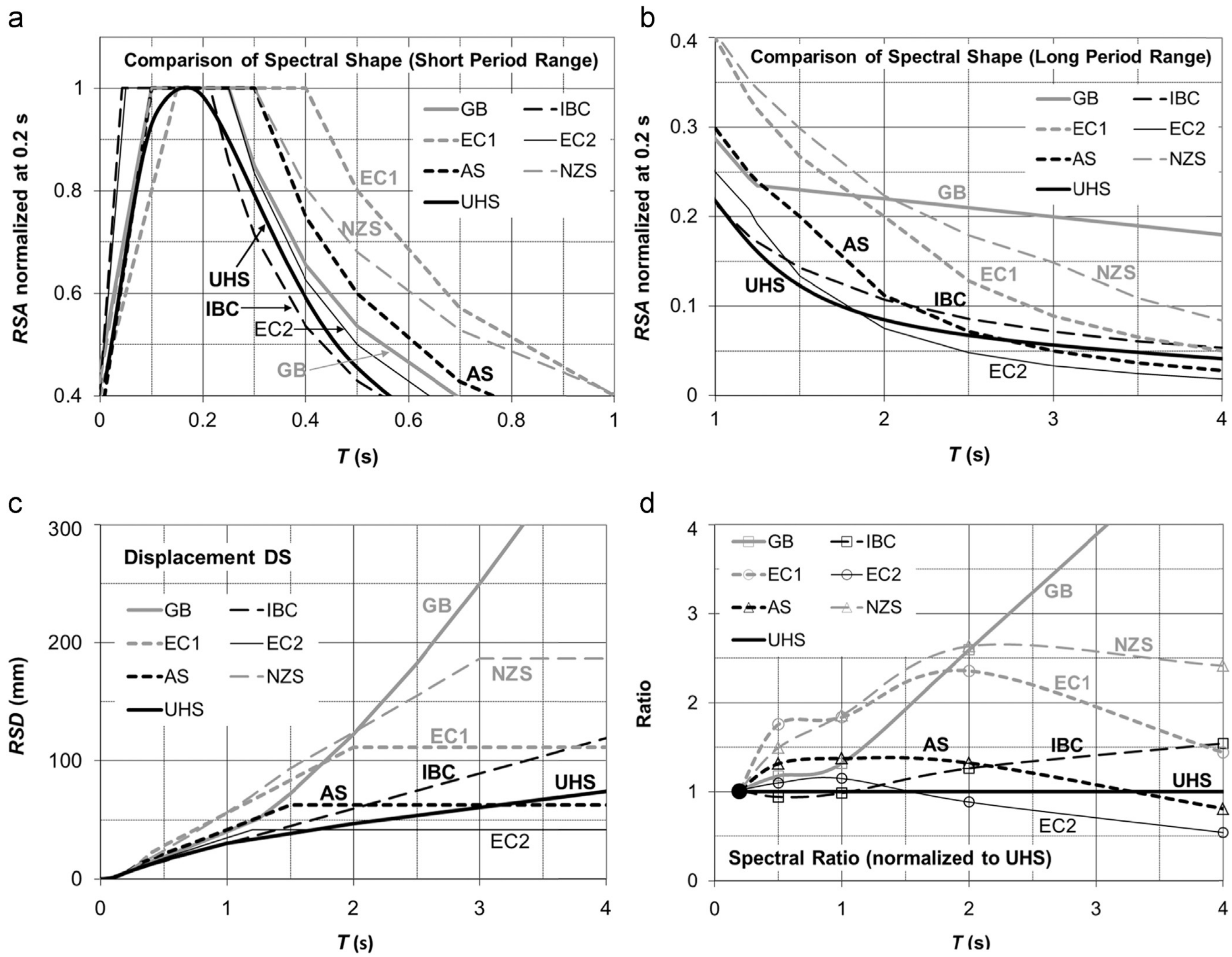

Fig. 2. DS model for rock sites constructed based on various codes of practice, in comparison with the UHS: (a) RSA – short-period range (0–1 s); (b) RSA – long-period range (1–4 s); (c) RSD – whole-period range; and (d) spectral ratio (normalized to UHS).

Table 3
Ratio of spectral values at 0.5 s and 2.0 s of various codified DS to the corresponding values of the UHS, and the corner periods T_1 and T_2.

Code	AS	EC1	EC2	GB	IBC/ASCE	NZS	UHS
Ratio at 0.5 s	1.32	1.76	1.10	1.18	0.94	1.50	**1.0**
Ratio at 2.0 s	1.32	2.36	0.88	2.59	1.26	2.63	**1.0**
T_1 (s)	0.3	0.4	0.25	0.25	0.21	0.3	–
T_2 (s)	1.5	2.0	1.2	1.25	4.0	3.0	–

Likewise, the ratios of spectral values at 2.0 s of various DS to that of the UHS are shown in Fig. 2(d) and tabulated in Table 3. It ranges between 0.88 (EC2) and 2.63 (NZS) amongst the six DS models. The greater overestimation (as compared to the ratio at 0.5 s) of EC1 and NZS is attributed to the "propagated" effects of the larger values of T_1, coupled with the larger values of T_2 (Table 3). The more conservative decreasing functions (in the RSA format) that are adopted in GB and NZS apparently contribute significantly to the overestimation.

4. Closing remarks

When a DS model for reference (rock) site is to be developed for a country or a city, it is recommended to select scaling parameters at more than one period values in order to reflect the spatial distribution of seismicity. Meanwhile, the values of corner periods should be decided based on the earthquake scenarios that are representative of the considered level of probability of exceedance. The set of values has to be determined on a city-specific or regional-specific basis, and could not be directly borrowed from a particular code of practice that was originally developed for another region. Blindly adopting a DS model in a code might lead to inadequate design or unnecessary conservatism.

Displacement-based design requires a reliable displacement DS for a wide range of natural periods. Hence, the displacement DS that is converted from the acceleration DS has to be realistic in both spectral shape and amplitude level. Importantly, the equation forms adopted in the intermediate-to-long period range would lead to significant differences in the displacement demand for medium- and high-rise buildings, but their significance is usually undermined in the RSA format.

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