A comparative study of design seismic hazard in major national codes

Abstract

The codes, invariably, define the design seismic hazard in terms of an idealized acceleration response spectra, which is scaled to the desired hazard level either using PGA or spectral ordinates corresponding to different period (usually at 0.2 sec and 1 sec). Design hazard levels are usually characterised by a return period or exceedence rate, and are associated with desired performance levels. Some of the codes are very clear about the return periods considered for design, but all the codes are vague about the intended performance objectives. Another important issue associated with design hazard is the effect of local soil strata. Currently, the codes handle this issue by classifying sites into different classes and proposing site (amplification) factors to scale the design spectra. Lately, displacement-based seismic design is becoming popular, for earthquake resistant design of structures. Design displacement spectrum is the key input in displacement based design, and applicability of displacement spectrum derived from code design spectra needs to be evaluated. This paper presents a comparative study of the design hazard levels, site classifications, and corresponding design response spectra specified by four major codes, viz. ASCE7, Eurocode 8, NZS 1170.5 and IS 1893. The design displacement spectra based on code spectra also compared with the empirically obtained displacement spectra using Next Generation Attenuation relationship.

Keywords: Seismic Design, Design Codes, Seismic Hazard, Response Spectra, Displacement spectra, Site Amplification

1. Introduction

All the current national codes for seismic design are based on a prescriptive Force-Based Design methodology using elastic design. In this prescriptive methodology of design, specification of design seismic hazard is the most crucial issue, which governs the design forces and hence the actual performance of the structures during earthquake. It is noted that the different codes still differ widely on this crucial issue.

The codes, invariably, define the design seismic hazard in terms of an idealized acceleration response spectra, which is scaled to the desired hazard level either using PGA or spectral ordinates corresponding to different period (usually at 0.2 sec and 1 sec). Design earthquake levels are usually characterised by a return period or exceedence rate and are associated with some specified performance levels. Some of the codes are very clear about the return periods considered for design earthquake, but all the existing codes are vague about the intended performance objectives. Another important issue associated with design hazard is the effect of local soil strata. Currently, the codes handle this issue by classifying sites into different classes and proposing site (amplification) factors to scale the design spectra. Historically, the earthquake resistant design of structures is based on estimated forces, duly reduced for inelastic energy dissipation. As force is poor indicator of damage in a structure, displacement-based design is becoming more popular. However, this concept is yet to find place in design offices, and lack of design guidelines is the main hurdle in this. Specification of design displacement spectra is one of the key tasks in this direction.

This paper presents a comparative study of four major national seismic design codes and examines applicability of displacement spectra derived from code specified design spectra, to displacement-based design, as the code spectra are originally intended for Force Based Design. The issues examined in the study include seismic hazard, site classification, design response spectra. The codes considered in the present study include the American code (ASCE7-05 2006), Eurocode 8 (EN1998-1 2004) and New Zealand Standard (NZS1170.5 2004), as these are currently the most advanced and widely used codes of the world. As most South Asian countries refer to the Indian codes, IS1893-Part1 (2002) has also been included in the study.

2. Specification of hazard

Codes specify design seismic hazard in terms of spectral ordinate(s). All the code considered for study, except ASCE 7 specify hazard in terms of peak ground acceleration (PGA). However, definition and terminology vary from code to code. Eurocode 8 refers it as reference peak ground acceleration or design ground acceleration. IS 1893 refers it as zone factor or EPGA and NZS 1170.5 refer it as hazard factor. Contrary to other codes, ASCE 7 specifies the hazard in terms of spectral accelerations, S_S and S_1 at 0.2*sec* and 1*sec* periods, respectively.

Different codes vary significantly in defining the design hazard level (i.e. return period or exceedence rate associated to design earthquake). Eurocode 8 as well as NZS 1170.5 define seismic hazard at a return period of 500 years (approximately corresponding to10% probability of exceedence in 50 years). Eurocode 8 specifies an importance factor, γ_I to scale seismic hazard to other return periods, given as $\gamma_I = (P_L/P_{LR})^{-1/k}$, where P_L and P_{LR} are the target and reference probabilities of exceedence, respectively, in given years, and k depends on the seismicity. NZS 1170.5 directly provides conversion factors corresponding to various return periods. ASCE 7 specifies seismic hazard at maximum considered earthquake (MCE) and corresponding probability of exceedence is 2% in 50 years in most of the area in US, except coastal California (Leyendecker et al. 2000). A factor of 2/3 is recommended by ASCE 7 (2006) to scale the MCE hazard to design seismic hazard. However, Leyendecker et al. (2000) have shown that a constant reduction of MCE hazard results in different probability of exceedence in different parts. This problem is addressed in the 2010 revision of ASCE 7 (ASCE7-10 2010) by considering risk targeted MCE hazard. This approach is not considered herein, as other national codes haven't adopted it yet. IS 1893 specifies design hazard as 0.5 times the MCE hazard but it does not specify probability of exceedence for design seismic hazard or for MCE hazard.

3. Site classification

Local subsoil plays an important role in amplitude of ground motion and shape of the design response spectrum (Seed et al. 1976; Seed et al. 1988; Idriss 1990; Idriss 1991). Design codes consider the effect of soil amplification by dividing soils into different classes based on geotechnical parameters and assigning corresponding amplification factors. ASCE 7 and NZS 1170.5 divide soils into five types (A–E), whereas Eurocode 8 specifies four site types (A-D). IS 1893 has only three broad soil types (I-III). In addition to this, Eurocode 8 and ASCE 7 define separate classes for soils susceptible to liquefaction and plastic flow. Soils can be classified based on one or more classification parameter. All codes, except IS 1893 differentiate soils based on average shear wave velocity ($v_{s,30}$), SPT value (N) and unconfined shear strength (C_u). In addition to this, NZS 1170.5 also classify soil based on Low-amplitude natural period (T_n) and unconfined compressive strength (q_u). Recognizing the role of depth of soil in ground motion characteristic (Sun et al. 2005; Kamatchi et al. 2010), NZS 1170.5 classifies soil types C and D on the basis depth of soil, in addition to T_n. IS 1893 classifies soil based on SPT values, only.

Table 1 and *Table 2* show the comparison of soil types of various codes, with respect to SPT values and shear wave velocity, respectively. Similarities in site classification for stiff/soft clay sites can be observed. Soft rock, stiff clay and soft clay of ASCE 7 are similar to Type B, Type C and Type D, respectively of Eurocode 8. However, there are considerable differences in rock/hard rock sites. This may be attributed to different types of rock sites in different countries/regions (Weatherill et al. 2010). The broad parity of soil types of various codes with ASCE 7 site types is drawn as described in Tables 1 and 2, and used in further study.

Table 1. Comparison of soil classification of various codes with respect to SPT value (N).

ASCE 7	SPT Value, N	Eurocode 8	SPT Value, N	IS 1893	SPT Value, N
Type C	> 50	Type B	> 50	Type I	> 30
Type D	50-15	Type C	50-15	Type II	30-10
Type E	<15	Type D	<15	Type III	< 10

Table 2. Comparison of soil classification of various codes with respect to shear wave velocity

<table>
<tr><th>ASCE 7</th><th>Shear wave velocity, v_{s30} (m/s)</th><th>Eurocode 8</th><th>Shear wave velocity, v_{s30} (m/s)</th><th>NZS 1170.5</th><th>Shear wave velocity, v_{s30} (m/s)</th></tr>
<tr><td>Type A (Hard rock)</td><td>> 1524</td><td rowspan="2">Type A</td><td rowspan="2">> 800</td><td>Class A (Strong rock)</td><td>> 1500</td></tr>
<tr><td>Type B (Rock)</td><td>762–1524</td><td rowspan="2">Class B (Shallow soil sites)</td><td rowspan="2">> 360</td></tr>
<tr><td>Type C (Soft rock)</td><td>366–762</td><td>Type B</td><td>360–800</td></tr>
</table>

Type D (Stiff soil)	183–366	Type C	180–360	Class C (Shallow soil sites)/ Class D (Deep or soft soil sites)	360–150
Type E (Soft clay soil)	< 183	Type D	< 180	Class E (Very soft soil sites)	< 150

4. Design Response Spectra

4.1 Acceleration response spectra

Design spectrum depends on level of ground motion expected at site and local sub-soil. Codes specify standard spectral shapes which are scaled for PGA or other spectral ordinates and amplification factors corresponding to site classes. All codes, except ASCE 7 specify amplification factors for various soil types, independent of ground shaking levels. ASCE 7 considers the amplification effect more rationally by specifying amplification factors depending on amplitude of spectral ordinates. Eurocode 8 attempts to consider this effect by specifying two different spectra, based on expected surface-wave magnitude (M_s) at site, namely Type I ($M_s > 5.5$) and Type II ($M_s < 5.5$).

Figure 1 shows the normalized amplification factors at short period (0.2 *sec*) and long period (1 *sec*) for 0.2*g* and 0.5*g* PGAs, for sites corresponding to ASCE 7 site classes B-E. Normalization is done with respect to ASCE 7 site class B. For 0.2*g* PGA, short period and long period amplification of ASCE 7 sites is more than or equal to other codes amplification. All codes, except ASCE 7 ignore the effect of amplitude of ground motion. In ASCE 7 amplification factors reduce with increase in PGA. Generally, the amplification in long period range is larger than that in short period range. For the considered range of parameters, the maximum values of short period and long period amplification factors are 1.7 and 3.2, respectively, for ASCE 7 soil site E.

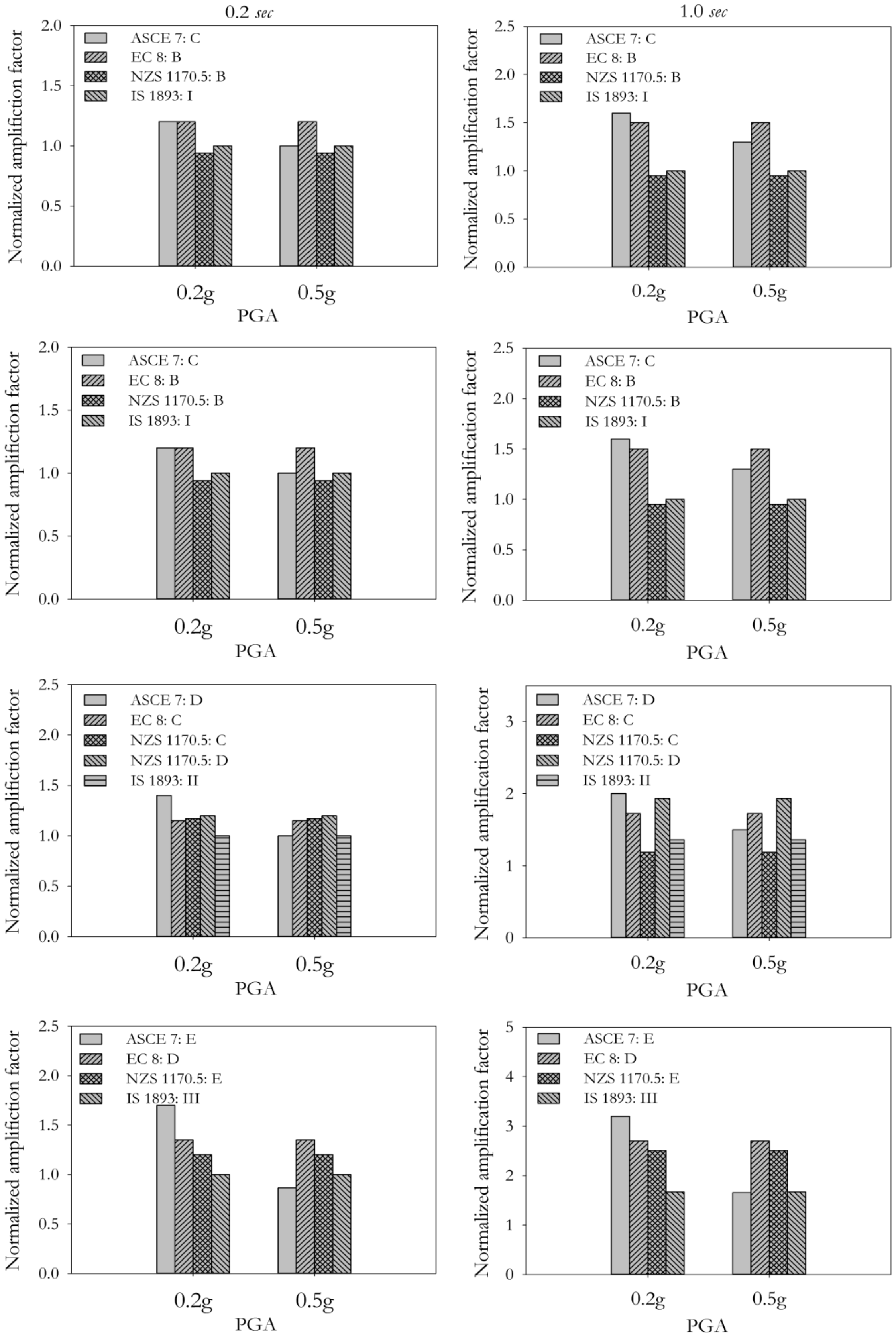


Figure 1. Comparison of short period (0.2 sec) and long period (1sec) amplification considered by various codes for ASCE 7 site classes B (top)-E(bottom) for 0.2g and 0.5g PGAs. The amplification factors are normalised w.r.t. the factors for in ASCE 7 site class B.

Figure 2 shows the comparison of acceleration response spectra for ASCE 7 site classes (B-E) and equivalent soil types of other codes. All the spectra are plotted up to 4 sec, as all codes specify spectra for this period range. Eurocode 8 type I spectrum is considered, as it is similar to other codes. There is considerable variation in spectra for all site classes, except for ASCE 7 class B. NZS 1170.5 specifies same spectrum for soil types A and B. IS 1893 does not consider amplification in short period range.

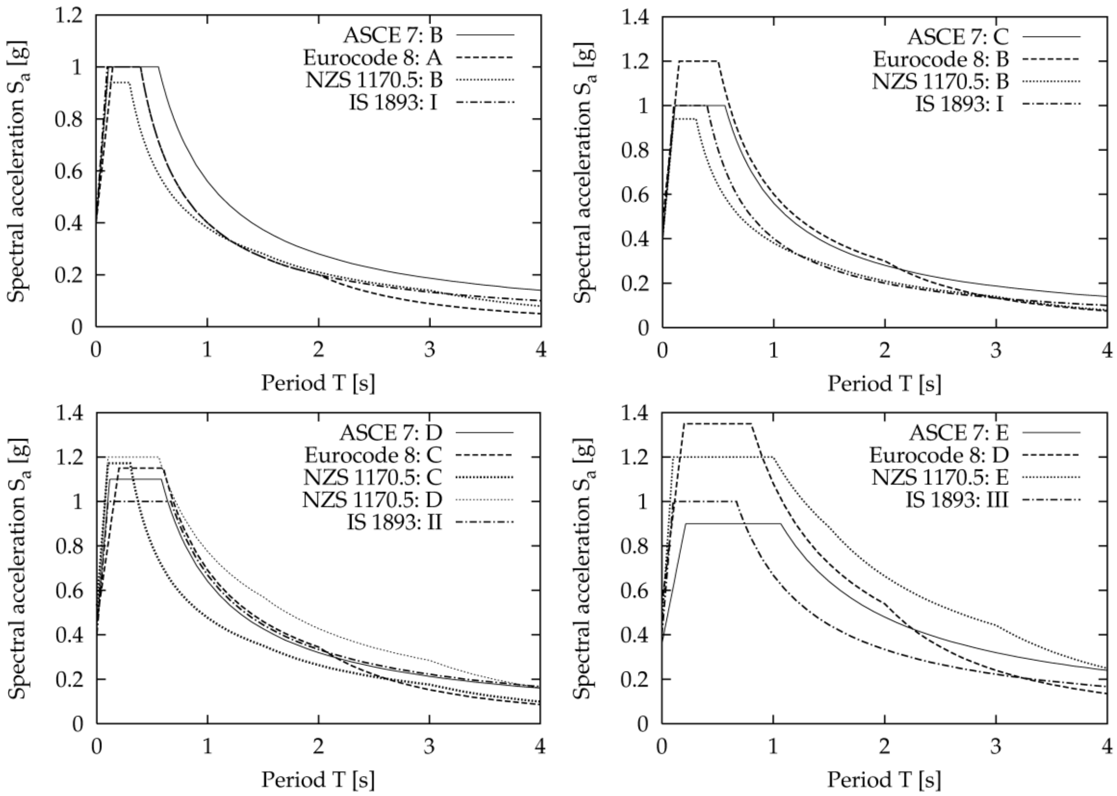


Figure 2. Comparison of normalized response spectra of various seismic design codes for ASCE 7 site classes B (top left) –E (bottom right) for a 0.4g PGA.

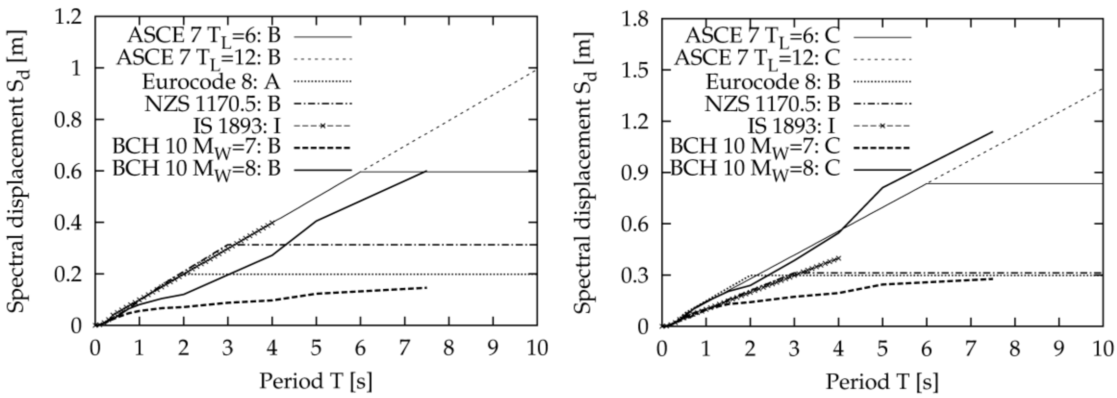
4.2 Displacement spectra

Displacement is now widely recognized as the most important design parameter and damage indicator (Moehle 1992; Calvi and Kingsley 1995; Medhekar and Kennedy 2000; Xue and Chen 2003; Priestley et al. 2007). In conventional force-based design also, interstory drift is an important criterion, which may govern structural design in many cases. Priestley et al. (2007) have shown that fundamental periods of even moderately tall buildings lie in the displacement-controlled range of the response spectrum. Corner period between the velocity-controlled and displacement controlled ranges is the one of the governing parameter in construction of displacement spectrum. It is a function of source mechanism, earthquake magnitude and epicentral distance (Bommer and Elnashai 1999; Tolis and Faccioli 1999; Faccioli et al. 2004; Akkar and Bommer 2007) and difficult to estimate. ASCE 7 specifies it in the range of 4-16 sec, depending on local seismicity and provide separate map for the same. FEMA450-Part2 (2003) specifies the tentative corner periods corresponding to magnitude (M_w) of earthquake.

EC 8 and NZS 1170.5 specify constant corner periods as 2 sec and 3 sec, respectively. IS 1893 does not specify displacement-controlled range of spectrum and hence corner period.

Figure 3 shows displacement spectra of the four investigated codes, along with that obtained from Next Generation Attenuation (NGA) empirical relationship by Bozorgnia et al. (2010) for magnitude, M_w = 7 and 8, for ASCE 7 site classes B – E. All the spectra are plotted for a PGA equal to 0.4g. In case of empirical response spectrum for given M_w, rupture distance (R_{RUP}) has been adjusted to obtain PGA value of 0.4*g* on ASCE soil type B. Response spectra for soil types C, D and E are estimated by changing corresponding shear wave velocities ($v_{s,30}$) and keeping other parameter same as for soil type B. The code design displacement spectra are estimated from acceleration spectra, using displacement acceleration relationship. For the ASCE 7 spectra, the value of the corner periods (T_L) have been considered as 6 and 12 *sec*, consistent with magnitude, M_w=7 and 8, respectively (FEMA450-Part2 2003).

A comparison of displacement spectra obtained from the design spectra of the investigated codes show even more remarkable differences than the acceleration spectra. Figure 3 shows the drastic differences in displacement spectra and the role of the corner period in estimating displacement spectrum. It is interesting to observe that the ASCE 7 spectra is conservative in all the cases for M_W =7. For M_W =8, the displacement spectra obtained from ASCE 7 design spectra are close or slightly conservative, as compared to empirical spectra, for all soil types, except for site class D, where the ASCE 7 spectra is on non-conservative side. For other codes, there are significant differences in design displacement spectra, which are generally on non-conservative side as compared to empirical spectra, except for ASCE 7 site class D. In case of ASCE 7 soil type D, Eurocode 8:B and NZS 1170.5:C spectra are closely matching with empirical spectra for M_w=7. ASCE 7 appears to be more realistic on specification of corner periods, as compared to other codes. IS 1893 does not specify displacement controlled range of spectrum and hence corner period, whereas the corner periods specified by Eurocode and NZS 1170.5 appear to be too low and effect of magnitude on corner period is completely ignored. Recently, this issue has attracted significant attention (Faccioli et al. 2004; Akkar and Bommer 2007; Priestley et al. 2007) and the need to review and revise code design spectra to obtain reliable estimates of displacement has been highlighted.



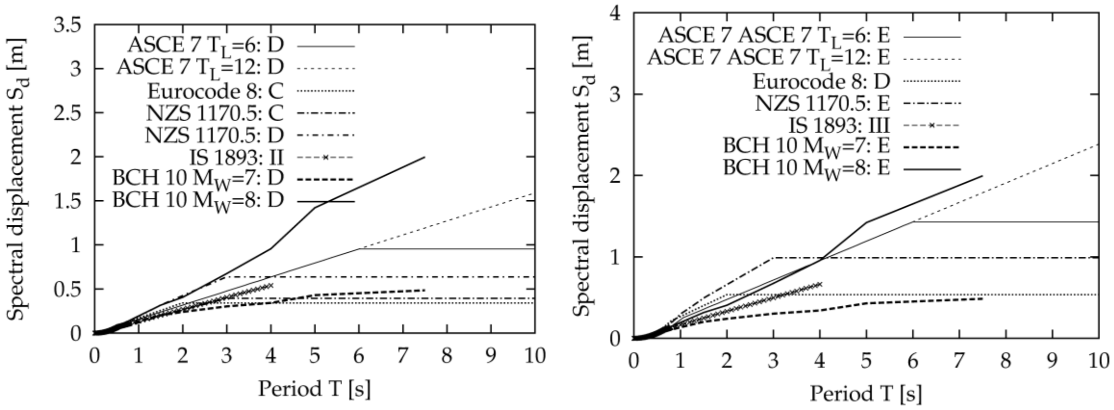


Figure 3. Comparison of displacement spectra of various seismic design codes for ASCE 7 site classes B (top left)-E (bottom right) for a 0.2g PGA.

5. Conclusions

A comparative study of the design hazard levels, soil types, and corresponding design response spectra specified by four major codes, viz. ASCE7 (America), Eurocode 8 (Europe), NZS 1170.5 (New Zealand) and IS 1893 (India), has been presented. The study also compared the design displacement response spectra derived from code spectra, with the empirically generated displacement spectra. There are significant variations in aforementioned code provisions. Provisions of IS 1893 are not up to the sate-of-the-art. NZS 1170.5 provides a more refined site classification. It differentiates soils based on low-amplitude period and depth of soil, also. Only ASCE 7 considers the effect of ground motion amplitude on soil amplification. Corner period between constant-velocity and constant-acceleration is one of the important parameter governing the construction of displacement spectra. Codes vary significantly on this issue. ASCE 7 provisions on corner period appear to be more realistic as compared to other codes. Eurocode 8 and NZS 1170.5 specify constant values of corner period, ignoring the effect of seismotectonic setup. IS 1893 does not specify any displacement-controlled range and hence corner period. Considering the wide differences in code based spectra, there is an urgent need to review and revise the code design spectra, to obtain reliable estimates of displacement for displacement based design.

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