Journal of Earthquake Engineering, 21:169–180, 2017

ISSN: 1363-2469 print / 1559-808X online
DOI: 10.1080/13632469.2016.1157527

Technical Note: Practical Challenges Facing the Selection of Conditional Spectrum-Compatible Accelerograms

BEKİR ÖZER AY[1,2], MATTHEW JAMES FOX[2,3], and TIMOTHY JOHN SULLIVAN[4]

[1]Department of Architecture, Middle East Technical University, Ankara, Turkey
[2]EUCENTRE, Pavia, Italy
[3]ROSE programme, UME School, IUSS Pavia, Pavia, Italy
[4]Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand

There are various possibilities for the selection and scaling of ground motions for advanced seismic assessment of buildings using nonlinear response-history analyses. As part of an on-going project looking at building-specific loss assessment in Italy, this article highlights a number of challenges currently facing the use of conditional spectra for ground motion selection in practice, essentially related to the limited amount of seismic hazard information that is publicly available. To illustrate the points being made, the challenges faced when trying to develop conditional spectra and select spectrum-compatible accelerograms for a rock site in Napoli, Italy, are described and the seismic assessment results obtained for a number of reinforced concrete wall structures are presented. Aside from providing practitioners with an appreciation of the potential difficulty associated with using conditional spectra for record selection, this technical note should also motivate national authorities to provide more background information on national seismic hazard data and detailed guidance for record selection.

Keywords Ground-Motion Selection; Conditional Spectrum; Spectrum Compatible Accelerograms; RC Walls; Seismic Assessment

1. Introduction

Emerging performance-based earthquake engineering procedures, such as the PEER PBEE methodology [FEMA P-58, 2012], now offer engineers the opportunity to assess a variety of modern decision variables for a building, from intensity-specific measures of parameters such as repair cost and down time, through to time-based assessments of expected annual loss or the annual probability of collapse. Such probabilistic assessment frameworks are not restrictive on the type of structural analysis method. However, even though the possibility of using simplified analysis methods is foreseen [FEMA P-58, 2012; Sullivan *et al.*, 2014], most applications of the PEER PBEE methodology appear to utilise a multiple-stripes analysis [Jalayer and Cornell, 2002], in which nonlinear response-history analyses are conducted on a numerical model of the building using sets of ground motions, representative of

Received 02 January 2015; accepted 19 February 2016.
Address correspondence to Timothy John Sullivan, Department of Civil and Natural Resources Engineering, University of Canterbury, Private Bag 4800, Christchurch New Zealand. E-mail: timothy.sullivan@canterbury.ac.nz
Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/ueqe.

certain return period events. Such analyses furnish the engineer with information on a range of useful engineering demand parameters (EDPs), such as story drift or peak floor acceleration, that are then used in subsequent analysis stages of the PBEE assessment framework.

In order to apply a multiple-stripes analysis, the engineer must identify sets of ground motions that are compatible with the hazard at the site. There are many papers in the literature proposing different criteria and guidelines for ground motion selection (e.g., Beyer and Bommer, 2007; Iervolino *et al.*, 2008; Bradley, 2010; Baker, 2011; Ay and Akkar, 2012). Of the various proposals, the use of conditional spectrum-based ground-motion selection [Abrahamson and Al Atik, 2010; Baker, 2011; Lin *et al.*, 2013a] appears to be quite promising for building-specific seismic risk assessment and is becoming increasingly common. To this extent, USGS currently provides conditional mean spectra and given this, it could be expected that the engineering profession will be encouraged to start using conditional spectra to guide ground-motion selection in practice. However, as part of the on-going RELUIS project looking at building-specific loss assessment in Italy, this article highlights a number of challenges currently facing the use of conditional spectra for ground-motion selection in practice. A review of the conditional spectrum (CS) as a target for record selection is first described in Sec. 2, while Sec. 3 identifies issues that may be encountered when trying to apply the approach in practice, highlighting the potential impact of such issues on seismic assessment results for RC wall structures.

2. Use of Conditional Spectra for Record Selection

The conditional spectrum approach first identifies the expected response spectrum (with mean and variance) conditioned on the occurrence of a target spectral acceleration value for a period of interest, and then selects ground motions to match this spectrum. Figure 1 illustrates the manner with which a conditional spectrum, in this case constructed for a conditioning period, T^*, of 1.0 s, may differ from a uniform hazard spectrum (UHS) typically provided in seismic design codes. The UHS corresponds to an envelope of spectral ordinates with equal probabilities of exceedance at different periods and therefore does not correspond to a particular scenario earthquake. The conditional spectrum overcomes this shortfall by considering a single or multiple causal earthquake(s) obtained from seismic hazard disaggregation. This results in mean spectral ordinates that are typically less than the UHS at periods other than the conditioning period. Furthermore, by including the conditional variance, the conditional spectrum allows for an accurate representation

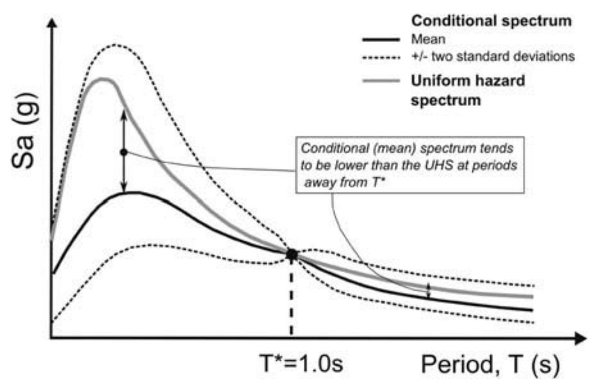

FIGURE 1 Comparison of a (hypothetical) uniform hazard spectrum and a conditional spectrum with $T^* = 1.0$ s.

of record to record variability in the selection and scaling of ground motions, which is important if the aim of nonlinear response-history analyses is to estimate the full probabilistic distribution of structural response.

In brief, the conditional spectrum can be constructed for a single earthquake scenario by first selecting an appropriate conditioning period and then identifying the intensity $Sa(T^*)$ corresponding to the return period of interest. An appropriate ground-motion prediction equation (GMPE) is then selected and used to calculate $\varepsilon(T^*)$, which is the number of standard deviations between $Sa(T^*)$ and the mean spectral acceleration predicted by the GMPE. The mean spectral acceleration from the GMPE is calculated using the magnitude and distance (and other relevant parameters) of the causal earthquake being considered. Once $\varepsilon(T^*)$ is known, correlation equations are used to determine the mean value of $\varepsilon(T)$ at all other periods of interest, thus giving the conditional mean spectrum. The same correlation equations can then be used to obtain the conditional variance of $\varepsilon(T)$, which once included with the conditional mean provides the conditional spectrum.

3. Potential Issues with the Application of the Conditional Spectrum Approach for Record Selection in Practice

As described in the previous section, there is a strong theoretical basis behind conditional spectra. However, there are a number of constraints, discussed herein, that may make their application challenging in practice. To illustrate the points made, reference will be made to the conditional spectra and compatible records that were selected as part of the displacement-based loss assessment research line of the Italian RELUIS project mentioned earlier.

3.1. Incomplete Disaggregation Information

The hazard information publically available in Italy is considered relatively detailed compared with that provided in other countries, with UHS provided for nine different return periods, for latitude and longitude points throughout the country, and with disaggregation information published by Barani *et al.* [2009]. The disaggregation information of Italian hazard provided by Barani *et al.* [2009] (and via personal communication) for exceedance of an *Sa* level at period values of 0.3, 0.75, 1.0, 1.5, and 2.0 s and for return periods (T_R) of 30, 50, 72, 101, 140, 201, 475, 975, 2475 years has been used in this study. Table 1 summarizes the mean surface wave magnitude (M_S) and source-to-site distance (R) values as well as spectral acceleration for the T_R values used in this study. However, while such information may seem refined to most structural engineers, this hazard and disaggregation information permits calculation of only the most approximate CS (i.e., a single GMPE with a single earthquake scenario) in terms of the scheme outlined in Lin *et al.* [2013a].

Complete disaggregation information from the probabilistic seismic hazard assessment (PSHA) process is often not likely to be available. In the case of the RELUIS project, only the mean and modal values of magnitude and distance were available. This brings forward the question of which central tendency measure to use in lieu of considering all causal earthquakes. Using the modal *M-R* pair is seismologically coherent since the event of a modal *M-R* pair reflects a real scenario. On the other hand, using the mean *M-R* pair (the approach used in this study) is mathematically consistent but the resulting scenario does not necessarily reflect a possible event for the specific site. It was found for this study that using mean *M-R* values yields smaller conditional mean spectrum ordinates by about 16 % when compared with using modal *M-R* values for the period range of $0.2T^*$ to $2.0T^*$ when

TABLE 1 Mean surface wave magnitude (Ms) and source-to-site distance (R) obtained from seismic hazard disaggregation for Napoli [Barani et al., 2009] for the return periods used in this study and corresponding spectral accelerations at five different periods of vibration

Period [s]		30 yr	50 yr	72 yr	101 yr	142 yr	201 yr	475 yr	975 yr	2475 yr
0.3	M_S	5.6	5.7	5.6	5.6	5.6	5.6	5.5	5.5	5.4
	R(km)	56.3	48.5	40.1	39.1	35.4	31.4	23.6	18.2	12.5
	Sa(g)	0.1016	0.1363	0.1668	0.1993	0.2338	0.2779	0.402	0.5319	0.733
0.75	M_S	5.9	6.1	6.2	6.2	6.2	6.3	6.3	6.3	6.3
	R(km)	72.5	66.4	61.3	59.6	57.1	54.5	48.5	44.3	39
	Sa(g)	0.0365	0.056	0.0733	0.0907	0.1076	0.1287	0.1915	0.2486	0.337
1.0	M_S	6	6.2	6.4	6.4	6.5	6.5	6.6	6.7	6.8
	R(km)	79.7	75.1	70.1	70.1	68.4	66.2	61.6	57.8	53.5
	Sa(g)	0.026	0.041	0.054	0.066	0.078	0.095	0.141	0.189	0.257
1.5	M_S	6.1	6.3	6.6	6.5	6.6	6.6	6.7	6.8	6.9
	R(km)	84.8	80.3	73.2	75.4	73.1	70.9	66.3	62.7	58.2
	Sa(g)	0.015	0.025	0.033	0.042	0.052	0.063	0.091	0.117	0.156
2.0	M_S	6	6.3	6.6	6.5	6.6	6.6	6.8	6.9	6.9
	R(km)	90.3	86.1	77.9	82.3	80.5	77.9	73.3	69.5	64.3
	Sa(g)	0.01	0.017	0.022	0.027	0.033	0.043	0.066	0.087	0.12

T^* is larger than 1.0 s. When the conditioning period is 0.3 s, the difference varies from –60 % (at $0.2T^*$) to +15 % (at $2.0T^*$) whereas it is less than ±10 % in the vicinity of 0.3 s.

In undertaking disaggregation for multiple-stripes analyses one should also note that disaggregation in terms of occurrence of a given intensity is preferable over disaggregation data provided in terms of the probability of exceeding a given intensity, as argued by Fox *et al.* [2015a]. However, this form of disaggregation is not commonly available, as was the case the RELUIS project, with the disaggregation data provided by Barani *et al*. [2009] being in terms of the probability of exceeding a given intensity.

3.2. Choice of a Suitable GMPE

Selection of a suitable GMPE for CS calculations may also be an issue that needs to be confronted in practice. Although this usually stems from the lack of GMPE disaggregation information, for some cases, the available prediction model(s) could be incompatible with the needs of the analyst. Barani *et al.* [2009] emphasized that their disaggregation considers only the Ambraseys *et al.* [1996] GMPE for rock conditions. Although it is consistent using the same GMPE both for hazard calculations and CS derivation, the Ambraseys *et al.* [1996] GMPE is only valid up to a 2.0 s period whereas the RELUIS project required estimates up to at least 4.0 s. Therefore, Ambraseys *et al.* [1996] is used for $T^* \leq 1.0$ s and for $T^* > 1.0$ s the Akkar *et al.* [2014b] GMPE is used.

The Akkar *et al.* [2014b] GMPE is relatively new and relies on the most recent pan-European strong-motion databank [Akkar *et al.*, 2014c] but it estimates the ground motion in terms of geometric mean, uses M_w as the magnitude scale and requires a faulting style parameter. Thus, the disadvantage of using this GMPE is the introduction of additional uncertainties. Ambraseys *et al.* [1996] estimates the ground motion in terms of the larger spectral ordinate of the horizontal components at each period, which can be designated as Sa_{ENV}. To be consistent with the hazard, this study used the Sa_{ENV} definition of spectral acceleration for both the CS calculation and record selection. For cases where the Akkar *et al.* [2014b] GMPE has been used ($T^* = 1.5$ s and 2.0 s), conversion between spectral ordinates from geometric mean (Sa_{GM}) to Sa_{ENV} has been carried out using the empirical formula given in Beyer and Bommer [2006]. The reader is referred to Beyer and Bommer [2006] for details on the limitations of these empirical formulas. The other parameter that needs additional consideration for the Akkar *et al.* [2014b] GMPE is the magnitude scale. Empirical equations proposed by Scordilis [2006] for conversion of $\mathrm{M_S}$ to $\mathrm{M_w}$ have been used for the Akkar *et al.* [2014b] GMPE. Finally, normal style-of-faulting, which is not used by Ambraseys *et al.* [1996], is assigned for Napoli in accordance with the recent seismic source model of Italy, ZS9 [Meletti *et al.*, 2008]. The difference between conditional mean spectra derived by using Ambraseys *et al.* [1996] and Akkar *et al.* [2014b] GMPE could become large (up to a factor of 1.4) for the period range from $0.2T^*$ to $2.0T^*$.

Another important concern related to the computation of the CS is the selection of a correlation coefficient model. For Ambraseys *et al.* [1996], the best option appears to be Cimellaro [2013] which is derived using the European Data and the GMPE presented by Ambraseys *et al.* [2005] (which also predicts the larger component of spectral acceleration, $\mathrm{Sa_{ENV}}$). However, this model is only valid up to 2.5 s. Consequently, for $T^* = 1.5$ s and $T^* = 2.0$ s (where Akkar *et al.*, 2014b is used as the GMPE), Akkar *et al.* [2014a] has been used. To illustrate the impact of the different choices of GMPE and correlation coefficient models, Fig. 2 shows four different conditional spectra for a conditioning period of $T^* = 1.0$ s. The four conditional spectra correspond to the four possible combinations of GMPEs and correlation coefficient models discussed previously. It can be seen that both the choice of GMPE and correlation coefficient model can have a significant impact on the

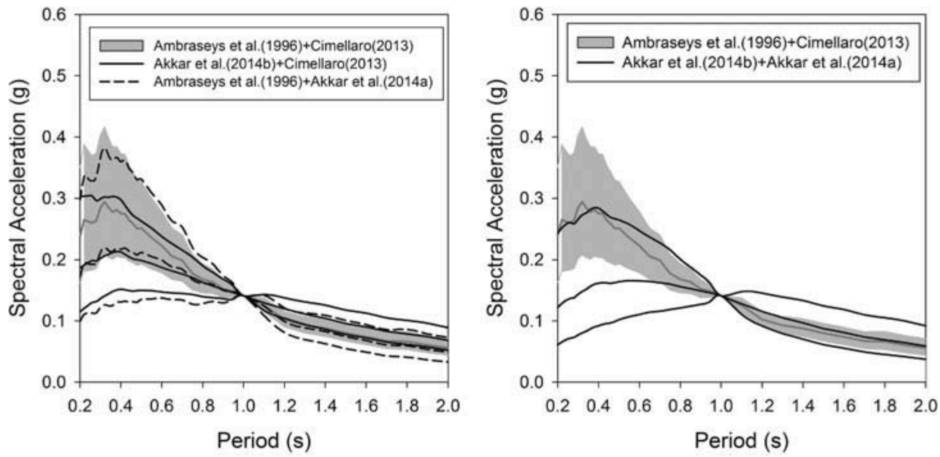

FIGURE 2 Comparison of conditional spectra found by using a different GMPE (left panel, solid line), a different correlation coefficient model (left panel, dotted line) and the combined effect of the choices on GMPE and correlation coefficient model (right panel).

resulting conditional spectra. It should be noted that additional considerations need to be made when considering correlation coefficients at high frequencies for hard-rock sites, as discussed by Carlton and Abrahamson [2014]; however, this is not expected to affect the results presented in this article.

3.3. Limits on the Number and Scaling of Accelerograms

Selection of a ground motion set that accurately matches the target CS is another component in obtaining unbiased estimation of structural response. In this study a candidate record bin is assembled, amplitude scaling carried out, and then the optimum ground-motion set, which has the best match with target CS, is selected. At the first step of candidate record identification, records without three components, having moment magnitude less than 4 or with maximum usable period less than 3.2 s have been rejected. A site constraint of $800 \leq V_{S30} \leq 2300$ m/s, which reduced the number of available records from 10288 to 320, was applied. This constraint was implemented since the hazard information used in this study has been derived specifically for rock sites. The chosen V_{S30} interval corresponds to the type A ground definition in Eurocode 8 (EC8) [CEN, 2004] for rock or rock-like conditions. Note that, especially moment magnitude but also other seismological characteristics (source-to-site distance and style-of-faulting) should be considered when constructing the ideal candidate set [Bommer and Acevedo, 2004; Ay and Akkar, 2012]. Nevertheless, this study relaxed these constraints to have a reasonable number of candidate accelerograms.

Additional selection constraints have been imposed to try to achieve accurate structural response estimations. Among these, the maximum usable period of the record is a critical constraint. Only records having a maximum usable period larger than $2.0T^*$ have been selected, except for $T^* = 2.0$ s because of the sudden decrease in the number of available records for the period value of 3.2 s. Thus, only for $T^* = 2.0$ s, the maximum usable period limit is taken as 3.2 s rather than 4.0 s. Finally, the number of records from one single event has been restricted. Bommer and Acevedo [2004] claimed that the dominancy of records from one single event should be prevented in order to not bias the structural response; however, they did not quantify the limit that ensures unbiased structural response.

Considering the number of available records and concerns regarding excessive use of the same event, the maximum number of records from one single event has been limited to one third of the required number of records.

An important concern related to the scaling process is the limit of the scaling factor. Among candidates, this study rejected the records that required a scaling factor (SF) larger than 4 (i.e., $0.25 \leq \text{SF} \leq 4$). The major reason behind this limit is to avoid excessive scaling factors as they may lead to unrealistic ground motions, even though the potential bias due to large scaling is uncertain (see, for example, Bommer and Acevedo, 2004; Luco and Bazzuro, 2007). Adopting these scaling factors, together with the other constraints described above, resulted in as few as 30 candidate ground motions for certain hazard levels, even though the original SHARE database [Yenier et al., 2010] used in this work includes 13,500 ground motions. It was also noted that the SHARE database provided a greater number of total candidate motions than the SIGMA, NGA-West1, and NGA-West2 databases, illustrating that the imposition of ideal constraints for ground motion selection may in fact be impractical.

Given the limits on the number of candidate records, some thought should also be given to the number of records used to match the target spectrum. Structural engineers will typically be interested in obtaining a reasonably small set of records (say 7–11) for each intensity level, so that analysis and post-processing time is limited. However, as computing power increases, one could argue that this is no longer justified and selection of a larger number of records should be required, since it will improve confidence in the dispersion estimates obtained from multiple-stripes analyses. Interestingly, the observations made above actually suggest that criteria adopted when identifying candidate records may impose a practical limit on the number of records that can be selected. To illustrate how conditional spectra may be affected by this approach, Fig. 3 compares the target and observed response spectra and corresponding variance for optimum record sets with 10 records (Napoli10) and 30 records (Napoli30) for a conditioning period of $T^* = 1.5$ s and a return period of 975 years. It can be seen for the Napoli30 set the match is rather poor at low periods due to the chosen constraints limiting the number of available ground motions to 34. On the other hand, a good match can be obtained for the Napoli10 set where

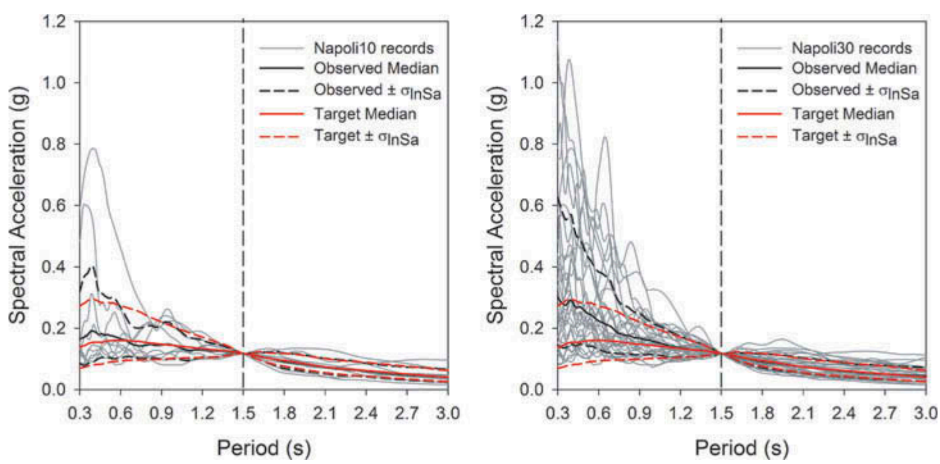

FIGURE 3 Comparison of observed data obtained for the optimum ground-motion bin containing 10 records (left) and 30 records (right) with target response spectrum and its variance (conditioned on $T = 1.5$ s at a return period of 975 years).

a much larger number of ground-motion combinations are possible. Even when sufficient candidate ground motions are available the choice of how many records to use is difficult and considered beyond the scope of the current work. Instead, readers are referred to Hancock *et al.* [2008], Buratti *et al.* [2011], and Cimellaro *et al.* [2011], among others.

3.4. Choice of a Suitable Conditioning Period

When using the CS as a target for ground-motion selection, caution should be exercised in the choice of a suitable conditioning period. Bradley [2012] demonstrated that in theory the choice of conditioning intensity measure does not affect the results of time-based assessments, but only if ground motions are selected correctly. Therefore, in the case where ground-motion selection is made based on only limited information there is the possibility that different choices of conditioning period will lead to different outcomes. This was examined by Lin *et al.* [2013b] who specifically focused on the choice of conditioning period when using the CS.

In the context of the current work, where only limited information is available for ground-motion selection, it may be the case that the choice of preferred conditioning period is not available. The analyst should then determine whether an alternative conditioning period is acceptable. To illustrate the factors that could affect this decision, three case study cantilever RC wall buildings are analyzed. The buildings correspond to three-, six-, and nine-story configurations and have first mode periods of vibration of 1.0, 1.5, and 2.0 s, respectively. Lumped plasticity models are developed in line with the recommendations of Priestley *et al.* [2007] and for details, see the description provided in Fox *et al.* [2015b], where it was also shown that predictions of drift and shear demand obtained using lumped plasticity models for regular cantilever walls were similar to those obtained using more refined models. For each building, the probability of exceeding a serviceability story drift limit of 0.3% was evaluated for a number of different available conditioning periods ($T^* = T_1$ and then the next closest available periods for which data was available). The results are shown in Table 2, where it can be seen that the choice of conditioning period has little impact on the probability of exceeding the drift limit.

In RC wall buildings, drift is dominated by the first mode of vibration and therefore a choice of conditioning period near T_1 is logical. However, other EDPs can be strongly influenced by multiple modes of vibration. In RC walls, base shear receives particularly large contributions from higher modes, especially in the post-elastic range when the first mode contribution is essentially capped due to plastic hinge formation (see Sullivan, 2010). This means that in practice the choice of T_2 as the conditioning period may be preferred over T_1. For each of the buildings the probability of exceeding a shear governed collapse limit state is calculated using both T_1 and T_2 as conditioning periods. The results provided in Table 3 show that for all buildings a higher probability of exceeding the collapse limit state is calculated when T_2 is used as the conditioning period.

TABLE 2 50-year probability of exceeding inter-story drift ratio governed limit state for case study buildings using different values of T^*

Building	$T^* < T_1$	$T^* = T_1$	$T^* > T_1$
3 story	44.8%	44.7%	40.7%
6 story	27.2%	28.2%	25.2%
9 story	23.6%	20.4%	–

TABLE 3 50-year probability of exceeding wall base shear governed limit state for case study buildings using $T^* = T_1$ and $T^* = T_2$

Building	$T^* = T_1$	$T^* = T_2$
3 story	23.4%	28.7%
6 story	11.1%	18.2%
9 story	7.8%	9.6%

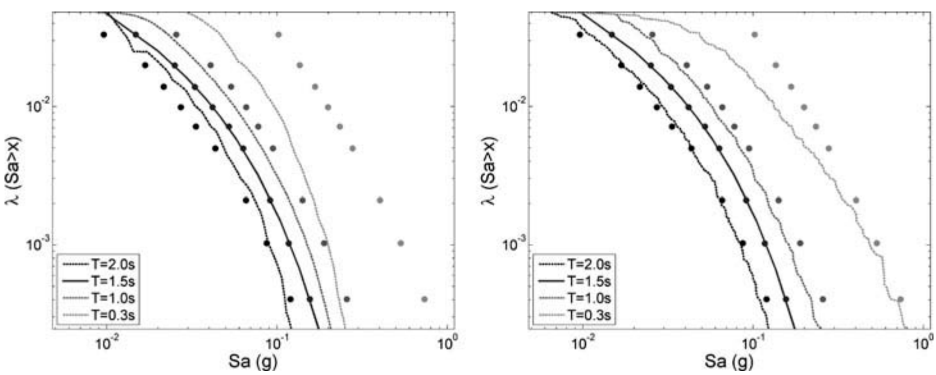

FIGURE 4 Hazard consistency check using the approach of Lin *et al.* (2013b) for $T^* = 1.5$ s. Calculated using target CS (left panel) and selected ground motions (right panel).

To better understand the results obtained in Tables 2 and 3, a hazard consistency check is carried out as per the approach presented in Lin *et al.* [2013b]. This involves calculating the implied hazard curve at an arbitrary period, T_i. This form of hazard consistency check does not guaranty accurate results will be obtained; however, as the true theoretical conditional distribution of $Sa(T_i)$ for a given level of $Sa(T^*)$ is unknown, it appears to be the suitable approach here. The check is carried out in this case for $T^* = 1.5$ s and the implied hazard calculated at periods of 0.3, 1.0, and 2.0 s. The results are shown in Fig. 4 for two cases: (a) calculations based on the target CS and (b) calculations based on the selected sets of ground motions. The implied hazard curves at periods of 1.0 and 2.0 s are a reasonably good match to those calculated from PSHA, which is owing to their close vicinity to the conditioning period. This match is reflected in the results obtained in Table 2. Conversely, for 0.3 s, the match to the hazard curve is very poor. The match is closer though in the case where the implied hazard curve is calculated form the selected ground motions; however, this is a result of a poor fit of the selected ground motions to the target in the low period range (see Fig. 3). Even though a good match is obtained in this case (Fig. 4, right panel) the difference in the calculated collapse probabilities for the six-story building (with $T_1 = 1.5$ s and $T_2 = 0.3$ s) is still significant.

The above results illustrate that even though theoretically the outcome of a performance assessment should not be affected by the choice of conditioning period [Bradley, 2012; Lin *et al.*, 2013b], it may well be because of practical constraints imposed during the record selection process. In addition, comparing results in terms of drift vs. shear, one notes that the choice of conditioning period may be relevant for some EDPs but not others (in this study, drift was less affected by the choice of T^* than shear). As such, the EDPs that are likely to be most critical to the outcomes of the risk assessment should be considered when selecting the conditioning period in practice.

4. Conclusions

The conditional spectrum is emerging as an effective tool for ground-motion selection in performance-based earthquake engineering. However, there are a number of practical challenges that may be faced by engineers using the conditional spectrum approach, as have been discussed in this work. Specifically, it has been shown that the availability of only limited disaggregation information means only approximate conditional spectra, considering a single earthquake scenario, can be calculated rather than accounting for all causal events. Similarly, approximations may be necessary regarding the choice of GMPE, particularly when the preferred choice does not cover the required period range, which will typically extend well beyond the selected conditioning period. These two factors, among others, mean that the choice of conditioning period can play a critical role and it was shown how different choices impact the calculated rate of exceeding drift and shear governed limit states in RC walls. It was also demonstrated for this particular example how constraints on candidate ground motions (such as maximum scaling factor) can severely reduce the number available for selection and subsequently make it difficult to match the target conditional spectrum. A choice must then be made between how many ground motions are desired and how good of a match to the target spectrum is needed. To avoid such difficulties as presented in this work, national authorities should be encouraged to provide more background information on national seismic hazard data and detailed guidance for record selection.

Funding

The authors gratefully acknowledge that the research leading to these results has received funding from the Italian Department of Civil Protection as part of the research line 7 of the 2014 RELUIS project and the 2014 EUCENTRE project C2.2.

The Scientific and Technological Research Council of Turkey (TÜBİTAK) provided financial support to the first author for conducting part of his post-doctoral research at the EUCENTRE in Italy.

References

Abrahamson, N. A. and Al Atik, L. [2010] "Scenario spectra for design ground motions and risk calculation," *9th US National and 10th Canadian Conference on Earthquake Engineering*, Toronto, Canada, p. 12.

Akkar, S., Sandıkkaya, M. A., and Ay, B. Ö. [2014a] "Compatible ground-motion prediction equations for damping scaling factors and vertical-to-horizontal spectral amplitude ratios for the broader Europe region," *Bulletin of Earthquake Engineering* **12**(1), 517–547.

Akkar, S., Sandıkkaya, M. A., and Bommer, J. J. [2014b]. "Empirical ground-motion models for point- and extended-source crustal earthquake scenarios in Europe and the Middle East," *Bulletin of Earthquake Engineering* **12**(1), 359–387.

Akkar, S., Sandıkkaya, M. A., Şenyurt, M., Azari Sisi, A., Ay, B.Ö., Traversa, P., Douglas, J., Cotton, F., Luzi, L., Hernandez, B., and Godey, S. [2014c] "Reference database for seismic ground-motion in Europe (RESORCE)," *Bulletin of Earthquake Engineering* **12**(1), 311–339.

Ambraseys, N. N., Simpson, K. A., and Bommer, J. J. [1996] "Prediction of horizontal response spectra in Europe," *Earthquake. Engineering and Structural Dynamics* **25**(4), 371–400.

Ambraseys, N. N., Douglas, J., Sarma, S. K., and Smit, P. M. [2005] "Equations for the estimation of strong ground motions from shallow crustal earthquakes using data from Europe and the Middle East: Horizontal peak ground acceleration and spectral acceleration," *Bulletin of Earthquake Engineering* **3**(1), 1–53.

Ay, B. Ö. and Akkar, S. [2012] "A procedure on ground motion selection and scaling for nonlinear response of simple structural systems," *Earthquake Engineering and Structural Dynamics* **41**(12), 1693–1707.

Baker, J. W. [2011] "Conditional mean spectrum: tool for ground-motion selection," *Journal of Structural Engineering* **137**(3), 322–331.

Barani, S., Spallarossa, D., and Bazzurro, P. [2009] "Disaggregation of probabilistic ground-motion hazard in Italy," *Bulletin of the Seismological Society of America* **99**(5), 2638–2661.

Beyer, K. and Bommer, J. J. [2006] "Relationships between median values and between aleatory variabilities for different definitions of the horizontal component of motion," *Bulletin of the Seismological Society of America* **96**(4A), 1512–1522.

Beyer, K. and Bommer, J. J. [2007] "Selection and scaling of real accelerograms for bi-directional loading: a review of current practice and code provisions," *Journal of Earthquake Engineering* **11**(1), 13–45.

Bommer, J. J. and Acevedo, A. B. [2004] "The use of real earthquake accelerograms as input to dynamic analysis," *Journal of Earthquake Engineering* **8**(Special Issue 1), 43–91.

Bradley, B. A. [2010] "A generalised conditional intensity measure approach and holistic ground-motion selection," *Earthquake Engineering and Structural Dynamics* **39**(12), 1321–1342.

Bradley, B. A. [2012] "The seismic demand hazard and importance of the conditioning intensity measure," *Earthquake Engineering and Structural Dynamics* **41**(11), 1417–1437.

Buratti, N., Stafford, P. J., and Bommer, J. J. [2011] "Earthquake accelerogram selection and scaling procedures for estimating the distribution of drift response," *Journal of Structural Engineering (ASCE)* **137**(3), 345–357.

Carlton, B. and Abrahamson, N. [2014] "Issues and approaches for implementing conditional mean spectra in practice," *Bulletin of the Seismological Society of America* **104**(1).

Cimellaro, G. P. [2013] "Correlation in spectral accelerations for earthquakes in Europe," *Earthquake Engineering and Structural Dynamics* **42**(4), 623–633.

Cimellaro, G. P., Reinhorn, A. M., D'Ambrisi, A., and De Stefano, M. [2011] "Fragility analysis and seismic record selection," *Journal of Structural Engineering* **137**(3), 379–390.

Comité Européen de Normalisation [2004] Eurocode 8, Design of Structures for Earthquake Resistance – Part 1: General Rules, Seismic Actions and Rules for Buildings, EN 1998-1, CEN, Brussels, Belgium.

FEMA [2012] "Next-generation methodology for seismic performance assessment of buildings," FEMA P-58, *Applied Technology Council for the Federal Emergency Management Agency*, Washington D.C.

Fox, M. J., Stafford, P. J., and Sullivan, T. J. [2015a] "Seismic hazard disaggregation in Performance-Based Earthquake Engineering: occurrence or exceedance?," *Earthquake Engineering and Structural Dynamics*, published online, doi: 10.1002/eqe.2675.

Fox, M. J., Sullivan, T. J., and Beyer, K. [2015b] "Evaluation of seismic assessment procedures for determining deformation demands in RC walls," *Earthquakes and Structures* **9**(4), 911–936.

Hancock, J., Bommer, J. J., and Stafford, P. J. [2008] "Numbers of scaled and matched accelerograms required for inelastic dynamic analyses," *Earthquake Engineering and Structural Dynamics* **37**(14), 1585–1607.

Iervolino, I., Maddaloni, G., and Cosenza, E. [2008] "Eurocode 8 compliant real record sets for seismic analysis of structures," *Journal of Earthquake Engineering* **12**(1), 54–90.

Jalayer, F. and Cornell, C. A. [2002] "Alternative non-linear demand estimation methods for probability-based seismic assessments," *Earthquake Engineering and Structural Dynamics* **38**(8), 951–972.

Lin, T., Harmsen, S. C., Baker, J. W., and Luco, N. [2013a] "Conditional spectrum computation incorporating multiple causal earthquakes and ground-motion prediction models," *Bulletin of the Seismological Society of America* **103**(2A), 1103–1116.

Lin, T., Haselton, C. B., and Baker, J. W. [2013b] "Conditional spectrum-based ground motion selection. Part I: Hazard consistency for risk-based assessments," *Earthquake Engineering and Structural Dynamics* **42**(12), 1847–1865.

Luco, N. and Bazzurro, P. [2007] “Does amplitude scaling of ground motion records result in biased nonlinear structural drift responses?,” *Earthquake Engineering and Structural Dynamics* **36**(13), 1813–1835.

Meletti, C., Galadini, F., Valensise, G., Stucchi, M., Basili, R., Barba, S., Vannucci, G., and Boschi, E. [2008] “A seismic source zone model for the seismic hazard assessment of the Italian territory,” *Tectonophysics* **450**, 85–108.

Priestley, M. J. N., Calvi, G. M., and Kowalsky, M. J. [2007] *Displacement-Based Seismic Design of Structures*, IUSS Press, Pavia, Italy.

Scordilis, E. M. [2006] “Empirical global relations converting M_S and m_b to moment magnitude,” *Journal of Seismology* **10**, 225–236.

Sullivan, T. J. [2010] “Capacity design considerations for RC frame-wall structures,” *Earthquakes and Structures* **1**(4), 391–410.

Sullivan, T. J., Welch, D. P., and Calvi, G. M. [2014] “Simplified seismic performance assessment and implications for seismic design,” *Earthquake Engineering and Engineering Vibrations* **13**(1), 95–122.

Yenier, E., Sandıkkaya, M. A. and Akkar, S. [2010] “Report on the Fundamental Features of the Extended Strong-Motion Databank Prepared for the SHARE Project,” Earthquake Engineering Research Center, Middle East Technical University, Ankara, Turkey.