Challenges in the Selection and Scaling of Records for Seismic Analyses: A Geotechnical Engineer's Perspective

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ABSTRACT

Earthquakes can cause damage or even collapse to structures and the consequence of damage or failure dictates the acceptable level of seismic hazard. Uniform Hazard Response Spectra (UHRS) with certain probability level of exceedance is usually used to define seismic hazard. Seismic design codes either explicitly define UHRS, or provide adequate guidelines to develop site specific UHRS for critical structures. However, UHRS alone is not sufficient to represent seismic hazard and assess or predict seismic performance of structures. Records representing design earthquakes are required to predict seismic displacements and assess seismic performance. With increased reliance on performance-based design for infrastructures, time history analyses are becoming routine in seismic design. However, there is inadequate and sometimes conflicting guidelines on how to select and scale records. UHRS, although a key intensity parameter, is one among many earthquake and intensity parameters that may control seismic displacements. An unexhaustive list of these parameters may include earthquake magnitude, distance, site conditions, mechanism, Arias intensity, significant duration, cumulative absolute velocity, peak ground acceleration, velocity and displacement. Typically, scenario earthquakes representing the sources of hazard are obtained from seismic de-aggregation analyses, and defined in terms of magnitude-distance pairs. A suite of time histories is then selected from past earthquakes similar to the scenario earthquakes, and either uniformly scaled to approximately match the target spectra in the period range of interest, or modified to match the target spectra. Key challenges faced in the selection and scaling of the earthquake records include: how many earthquake records are sufficient to capture the epistemic uncertainty? Is uniform scaling or matching the target spectra better? Should UHRS or conditional mean spectra be used as target spectra? Are large scaling factors acceptable? How to prioritize and define ranges for various earthquake and intensity parameters? What is the impact of these parameters on the computed displacements; How to select records if the contributing sources of hazard are significantly different (for example, local crustal and mega subduction for a site located close to subduction zone)?

This paper presents an overview of the methods used in current practice for the selection and scaling of earthquake records, describes various challenges faced by the practitioners and their impact on the computed seismic displacements or seismic performance through examples. It also makes recommendation for selection and scaling of records.

1   INTRODUCTION

Earthquakes can cause damage or even collapse to structures and the consequence of damage or failure dictates the acceptable level of seismic hazard. Uniform Hazard Response Spectra (UHRS) with certain probability level of exceedance is usually used to define seismic hazard. Seismic design codes either explicitly define UHRS, or provide adequate guidelines to develop site specific UHRS for critical structures. However, UHRS alone is not sufficient to represent seismic hazard and assess or predict seismic performance of structures. Records representing design earthquakes are required to predict seismic displacements and assess seismic performance. These records are used as input in time history analyses. With increased reliance on performance-based design for infrastructures, time history analyses are becoming routine in seismic design. However, there is inadequate and sometimes conflicting guidelines are available on how to select and scale records.

UHRS, although a key intensity parameter, is one among many earthquake and intensity parameters that may control seismic displacements. An unexhaustive list of these parameters may include earthquake magnitude, distance, site conditions, mechanism, Arias Intensity, significant duration, cumulative absolute velocity, peak ground acceleration, velocity and displacement. Typically, scenario earthquakes representing the sources of hazard are obtained from seismic de-aggregation analyses, and defined in terms of magnitude-distance pairs. A suite of time histories is then selected from past earthquakes similar to the scenario earthquakes, and either uniformly scaled to approximately match the target spectra in the period range of interest, or modified to match the target spectra. Key challenges faced in the selection and scaling of the records include: How many records are sufficient to capture the epistemic uncertainty? Is uniform scaling or matching the target spectra better? should UHRS or conditional mean spectra be used as target spectra? are large scaling factors acceptable? how to prioritize and define ranges for various earthquake and intensity parameters? what is the impact of these parameters on the computed displacements; how to select records if the contributing sources of hazard are significantly different (for example, local crustal and mega subduction for a site located close to subduction zone)?

An overview of the methods used in current practice for the selection and scaling of records is presented along with

the various challenges faced by the practitioners and their impact on the computed seismic displacements or seismic performance through examples.

2 SEISMIC HAZARD ASSESSMENT (SHA) AND GROUND MOTIONS SPECTRA

Probabilistic or deterministic based approaches are normally used in Seismic Hazard Assessment (SHA) to derive site specific ground motions for the design of new structures or for the evaluation of existing structures. Deterministic based approaches are appropriate, if the seismic hazard arise from a known active fault whose characteristic parameters are known. However, known active faults on shore in Canada are rare and the seismic hazard at most places in Canada are dominated by diffuse networks of unknown or uncharacterized local crustal faults, except in Western Canada where the offshore faults also contribute significantly or dominate. Probabilistic based approach is typically used in Canada and in many places around the world to derive ground motions for design or assessment.

The results from the probabilistic hazard are expressed in terms of Uniform Hazard Response Spectrum (UHRS) with certain probability of exceedance. Probability of exceedance of 2% in 50 years is normally used in building codes and the same level is used for dams with "high" consequence of failure. Lower probability levels of 1% in 50 years or 0.5% in 50 years (i.e. 5,000-year return period or 10,000-year return period) are used for "very high" and "extreme" consequence category dams (CDA, 2013). The probability levels of 10%, 5% and 2% in 50 years are used for bridges categorized as other, major route and lifeline, based on their importance (CHBDC, 2014).

The UHRS from seismic hazard is the geomean of the two orthogonal horizontal components of accelerations. The UHRS from SHA are outcrop motions representative of underlying bedrock of firm stratum. Any local effects due to relatively softer foundation soils are determined through geotechnical ground response or dynamic deformation analyses.

3 DESIGN SPECTRUM AND EARTHQUAKE RECORDS

An earthquake record fully describes shaking from an earthquake, while the response spectrum describes only the peak or maximum response of a series of oscillators of varying natural frequency to the shaking. Response spectrum only partially describes the earthquake shaking but has been traditionally popular among designers, especially structural engineers who use response spectrum analysis routinely in the seismic design. Ground motion prediction equations (GMPEs) are an integral part of any SHA and they enable the development of the design spectrum. The GMPEs describe the response spectrum of ground shaking generated by the earthquake. Improvements in the SHA traditionally focused on the development of newer and improved GMPEs to develop only the response spectra. Time histories are not provided

as direct output of a SHA, although the records have been the basis of most commonly used GMPEs.

In practice, the records are developed for engineering analyses after the response spectrum is developed from SHA. The records are developed such that their response spectra closely match the design spectra developed from SHA, usually within the period range of interest. As the focus has traditionally been on the development of the spectra, there have been inadequate and sometimes conflicting guidelines on how to develop the records.

Structural engineers perform response spectrum and nonlinear time history analyses as part of seismic design. Response spectrum analysis is more routinely performed. As the response spectrum analysis does not require records, the SHAs normally stop at providing only the design spectrum, and most of the design codes either specify the design spectrum or provide guidelines to develop them. Structural nonlinear time history analyses are relatively uncommon and are usually reserved for major and complex structures in high seismic regions. They require records. This is not true in geotechnical analyses, as records are required in most of the analyses.

4 GEOTECHNICAL SEISMIC ANALYSES AND INPUT EARTHQUAKE RECORDS

In current practice, geotechnical engineers typically perform two types of analyses in the design and/or performance evaluation of critical or important facilities such as hydro dams, tailings dams, bridges, buildings and port structures. One is site or ground response analyses, and the other is dynamic deformation or dynamic soil structure interaction analyses using finite element (FEM) or fine difference (FDM) methods. The ground response analyses are used to develop design spectrum for structural analyses and to assess the potential for triggering liquefaction or strain softening. The design spectrum captures any amplification or de-amplification which may occur. The dynamic deformation or dynamic soil structure interaction analyses are used to determine the seismic displacements and to assess seismic performance of the structures under earthquake shaking. In these analyses, the foundation soil overlying the bedrock or firm ground is modeled with or without the superstructure at the top, and input ground motion is applied at the bedrock or firm ground level. To capture the epistemic uncertainties in the input motion, normally a suite of records is used instead of a single record. The number of records used in practice varies from three to thirty-three.

The ground response analyses are normally one dimensional, and the dynamic deformation or dynamic soil structure interaction analyses using FEM or FDM are two dimensional. Three dimensional analyses are uncommon in geotechnical practice and performed only when the geometry or other aspects of the problem warrant such analyses. Hence, a suite of single horizontal component records is usually sufficient for most geotechnical analyses. Use of seven to ten single component records is not uncommon in the 1D or 2D analyses. Sometimes a suite of vertical records is also used, for example for a gravity retaining wall founded on bedrock.

5   SELECTION AND SCALING OF RECORDS

Selection and scaling of records is an important step in dynamic analyses using time histories. Use of inappropriate or unrepresentative records can lead to misleading conclusions from the dynamic analyses. They can result in both conservative and unconservative prediction of seismic performance. Estimates of seismic performance of geotechnical structures such as mean or 84%ile of seismic displacements can be misleading if insufficient number of records are used. An in-exhaustive list of factors that should be considered in the selection and scaling of records are:

- Target spectrum (UHRS, Deterministic Spectrum or Conditional Mean Spectrum) and period range of interest
- Scenario earthquake(s)
- Earthquake source parameters: Earthquake magnitude, distance and type (focal mechanism)
- Earthquake intensity parameters: Arias intensity (AI), Significant Duration, Cumulative Absolute Velocity (CAV), Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), Peak ground Displacement (PGD)
- Site parameters: Site class or Vs30
- Natural or artificial records
- Method for scaling of records (uniform scaling or matching target spectrum)
- Scaling Factors
- Number of records
- Single, two or three component records

5.1   Target Spectrum: UHRS, Deterministic Spectra (DS) and Conditional Mean Spectra (CMS)

Target spectrum is often taken as the UHRS. DS is commonly used for sites where the dominant sources contributing to the hazard is clearly identified and their characteristics including the rate of activity are known. The CMS is becoming increasingly popular. This is in recognition of the fact that UHRS does not represent a particular scenario earthquake but can be considered as an envelope of several scenario earthquakes that pose hazard. Sometimes the hazard at the short period and long period represented by UHRS arise from distinct sources. i.e. The short period hazard is due to a low magnitude, short duration crustal earthquake, and long period hazard is due to large magnitude, long duration subduction earthquake. In this case, it may not be appropriate to select records from both sources and scale or match both to the same UHRS. If CMS is used instead of the UHRS, distinct sources contributing to the hazard at different periods can be represented. Typically, two or more CMS are used in practice.

Once the CMS are defined at the periods of interest, a suite of records representing each CMS can be selected and either uniformly scaled or matched to the CMS. Use of CMS facilitates selection of records that will have similar spectral shape as the CMS. However, its use will increase the number of records required for analyses. For geotechnical structures, the period of the structure varies during the earthquake shaking due to the nonlinear inelastic behavior of soils and CMS anchored at a selected two or three periods may not be adequate.
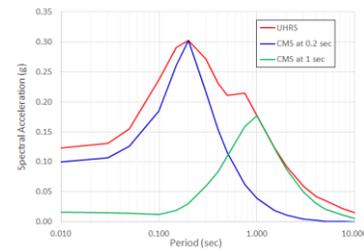
Figure 1. UHRS and CMS

5.2   Scenario Earthquake(s)

SHA provides the site-specific spectra for the design normally at 5% damping which is adequate in most geotechnical analyses. The site-specific spectra are used as the target spectra in the selection and scaling of records and is the primary input in the process. The response of structure depends on its fundamental mode or on a few dominant modes. Therefore, the range of period capturing the periods of dominant modes is more important than the entire spectrum. For earthen structures, the period range of interest typically varies between 0.5s to 1.0s, although depending on the foundation type (rock or soil), height and the stiffness, the period could be shorter or longer and range could expand to 0.3s to 2.0s.

Apart from the target spectrum, the definition of the scenario earthquake(s) is also equally important. The scenario earthquake is defined usually as earthquake magnitude-distance pair. Unlike in deterministic SHA, hazard arising from multiple sources are combined in probabilistic SHA. Seismic de-aggregation analyses are usually performed to identify the percentage contribution of hazard coming from different sources and usually expressed in terms of magnitude-distance pair (M-R) (plus information on the aleatory uncertainty in the GMPEs). The de-aggregation results will show whether single or multiple sources are contributing to the hazard at a particular period. In cases where multiple sources dominate at a particular period and/or if they vary over the period of interest, defining the scenario earthquake(s) will not be simple and defining a single M-R pair may not be appropriate. In this case, multiple scenario earthquakes are defined and used during the selection of records. There is no single parameter such as the maximum, mean, modal or 84th percentile values that can be used in the earthquake record selection although the use of mean value is not uncommon.

5.3   Earthquake Source Parameters

As the scenario earthquakes are defined in terms M-R pair and identified by the mechanism, these three parameters are important in the selection of candidate records. Among them, the magnitude is considered the most important although the mechanism is also important and cannot be ignored. However, due to lack of records satisfying all three, the distance parameter is often relaxed or a wider range is used. For magnitudes, typically, they are taken +/-

0.5 although relaxing to include +/-1 magnitude is not uncommon.

5.4   Earthquake Intensity Parameters

The intensity of earthquake shaking can be described using various intensity measures other than the peak ground acceleration (PGA) or spectral acceleration. These parameters include AI, significant duration, Cumulative Absolute Velocity (CAV), response spectrum intensity, characteristic intensity, Peak Ground Velocity (PGV) and Peak Ground Displacement (PGD). Guidelines or codes do not provide adequate guidance on how to develop selection criteria, which intensity measures are important or how to prioritize the parameters during the selection and scaling process. The importance of the duration of shaking has long been recognized as an important parameter in the liquefaction assessment or in the prediction of seismic displacements. It is indirectly represented by earthquake magnitude.

Arias intensity (AI) is a ground motion parameter that incorporates the effect of amplitude, frequency content and duration of ground motions and hence is considered a more reliable parameter than an acceleration amplitude to capture the potential destructiveness of the earthquake (Travasarou et al., 2003). Increasingly, the AI is being recognized as a good predictor of seismic performance or earthquake damage potential by many researchers as it can capture multiple characteristics of a ground motion. The importance of considering AI in the selection and scaling of records in simple rigid body sliding block based displacement analyses has been demonstrated by many. However, its importance in nonlinear time history analyses of earthen embankment has been demonstrated only by a few. Cumulative Absolute Velocity (CAV) is another parameter which is being recognized as an important parameter by many researchers in the last decade.

5.5   Site Parameters: Site Class or Vs30

In the selection of records, it is important to consider the site Vs30 of the candidate records. If the Vs30 candidate record site is similar to the Vs30 of the site under design, it will likely have the same spectral shape to the target spectra. This will avoid large or unnecessary scaling of the candidate records during the matching process. Records in the databases are dominated by records belonging to soft and stiff soil sites with relatively few records from rock or hard rock sites. Selecting records for structure on rock or hard rock is usually a challenge due to lack of adequate records.

5.6   Natural and Artificial Records

Candidate records for sites in seismically active regions are normally selected from past earthquakes, which occurred in similar tectonic setting, recorded in similar site conditions, and the shape and amplitude of spectra are similar to those of the target. In Canada, the site conditions are separated as either similar to Western North America (WNA) or Central or Eastern North America (CENA). Due to lack of records in the database representative of CENA conditions, especially for moderate to large magnitude earthquakes, selecting records for these conditions has been a challenge. Artificial algorithms are sometimes used.

5.7   Method for Scaling Records: Uniform Scaling or Spectral Matching

The records selected to represent the scenario earthquake(s) are either uniformly scaled to approximately match the target spectrum in the period range of interest, or modified to match closely. Uniform linear scaling preserves the frequency content and phasing of the original records. However, they could be lower or higher at certain periods that may not be preferred for geotechnical structures whose period varies over a range due to change in height, spatial variability of soil stiffness and due to the highly nonlinear inelastic behavior of soils. This issue is overcome with the use of a suite of records so that the average of the suite closely matches the target spectra. Both frequency and time domain matching procedures are available, although time domain matching is currently considered a preferred approach. In current practice, both procedures are used without any preference of one over the other.

5.8   Scaling Factors

Often at low probability hazard level (i.e. 10,000 year return period), the UHRS represents a rare event. Selecting an adequate number of natural records to represent low probability event has been a challenge due to the lack of records in the databases. In this case, the records have to be scaled up by a significant factor. However, the use of large scaling factors is not preferred. Not only will it make the time history not representative of a past earthquake, it may unduly increase the other intensity parameters such as the AI. A scaling factor of two will increase the AI by a factor of four as AI is the integral of the square of the acceleration. Scaling using significantly large or small factors may give good match to the target but may not give representative estimates for AI or other intensity parameters.

5.9   Number of Records

Use of a single record has long been recognized as being not adequate. However, the total number of records required to capture the uncertainties in the records is not clear. Codes and guidelines are either silent or provide varying recommendations. Canadian Dam Safety guidelines (2007 CDA) recommends 3 to 7 depending on the project. Canadian Bridge Code (2014 CHBDC) recommends 11 or more sets of three component records with no more than two from the same earthquake for "life line" bridges. This number is reduced to 7 single component for "major-route" bridges and to 3 single component for "other" bridges in the BC's supplement for the Canadian bridge code. 2015 National Earthquake Hazards Reduction Program recommends 7 pair (2015 NEHRP). Australian National Committee on Large Dams (2017ANCOLD) recommends at least 4 or 5 three

component records. National Building Code of Canada (2017NBCC) recommends 11 or more records

6 EXAMPLES

Four examples are presented below to demonstrate the issues and challenges faced with the selection and scaling of the records and their impact on the geotechnical seismic response of the structures.

6.1 Example 1: Earthdam Analyses with Two Suites of Time Histories

Seismic performance assessment of an earth dam in British Columbia, Canada was conducted using two suites of time histories. The dam is founded on low plastic silty soils that are susceptible to strain softening under seismic loading. The seismic hazard at the dam site at the design return period of 10,000 year is dominated by the local crustal earthquakes. The 10,000 year return period PGA is 0.64 g and the scenario earthquake is an event with M7.5. Suite 1 consists of eight records from seven crustal earthquakes. The selected records were modified in the time domain to match the 10,000 year return period target spectra using the computer program Ez-Frisk (2007). In the selection of records, the following parameters were considered: proximity of the scaled spectra of the candidate record to the target spectra prior to matching; Vs30 of the station; earthquake magnitude, significant duration, PGA, PGV and PGD. However, no criteria were applied to the other intensity parameters particularly for the AI. Figure 2a, 3a and 4a show the matched records, target and spectra of the matched records and the Husid plots for the matched records, respectively.

Suite 2 consists of seven records selected from seven crustal earthquakes. The selected records were not matched to the target spectra but uniformly scaled to approximately match the target spectra within the period range of interest. The period range of interest was taken as 0.5s to 1s, which is the expected natural period of the dam during shaking. During the selection and scaling of the records, the same earthquake and intensity parameters which were considered in the selection of Suite 1 records were also considered. In addition, the AI was also considered as a key parameter. Figure 2b, 3b and 4b show the scaled records, target and spectra of the matched records for the matched records and the Husid plots, respectively.
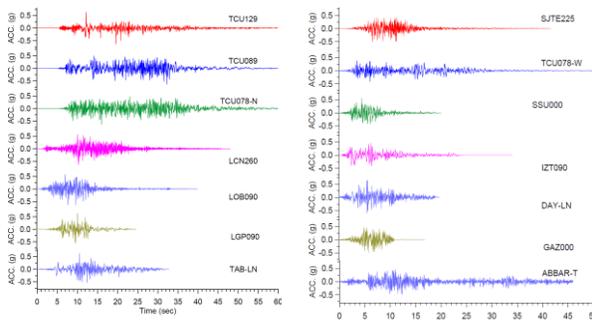
Figure 2a. Suite 1 records   Figure 2b. Suite 2 records
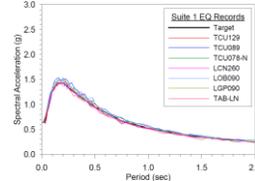
Figure 3a. Suite 1 spectra   Figure 3b.Suite 2 spectra
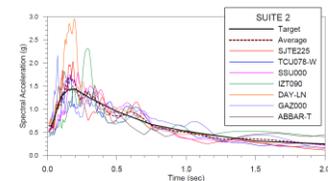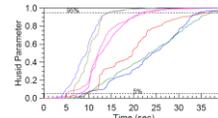
Figure 4a. Husid Plot for Suite 1   Figure 4b. Suite 2 Husid Plot
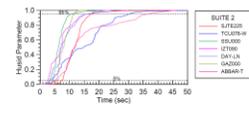
Ground response and liquefaction assessment were conducted using both suites of time histories to assess ground motion amplification and earthquakes induced cyclic stress ratios (CSR), which is a key input in the liquefaction assessment. The ground response analyses were conducted using the computer program Proshake (Edupro, 2005). In the Proshake analyses, the ground motions were applied as outcrop motions at the base of the model taken at the firm stratum.

Figures 5a and 5b show the peak horizontal acceleration (Amax) and CSR profiles from the ground response analyses, using the two suites of time histories. The range of Amax and CSR from the individual suites falls within a narrow band, although the second suite was generated by simple scaling. The average Amax and CSR from the two suites are generally similar with slightly higher prediction of Amax from the second suite. Figure 6 shows the spectra for the surface ground motions at the dam crest predicted using the two suites and the corresponding averages. There was more spread in the surface spectra predicted bu the Suite 2 records. However, the average spectra predicted by the two suites agree well.
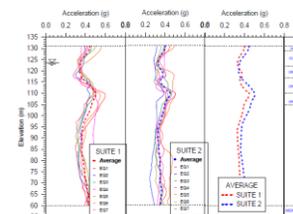
Figure 5a. Amax Profiles   Figure 5b. CSR Profiles
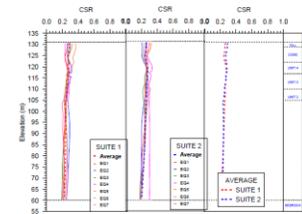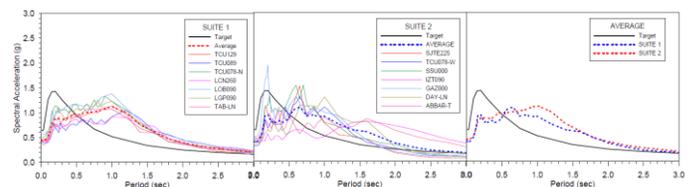
Figure 6. Surface spectra for Suite 1 and 2 records

Two types of seismic deformation analyses were conducted using both suites of time histories: (1) Newmark type sliding block analyses; and (2) Detailed seismic deformation analyses using an effective stress based constitutive model called UBCSAND developed at the

University of British Columbia (Byrne et al., 2004) and the computer program FLAC (Itasca, 2005). In the FLAC analyses, the nonlinear hysteretic and cyclic softening characteristics of the soils were captured. The input motions were applied in FLAC analyses as "within" motion velocity time histories at the base of the model taken at the firm stratum.

The Newmark type seismic displacements (Newmark, 1965) were computed for the both suites of records using the computer program Slammer developed by Jibson et al. (2013). The post-earthquake factor of safety against downstream instability was 1.1 and the corresponding yield acceleration for the dam was 0.04 g. Yield acceleration is the horizontal acceleration of the sliding mass required to bring the factor of safety to unity.

Figures 7a and 7b show the center crest displacement time histories from the FLAC analyses for Suites 1 and 2, respectively. Figures 8a and 8b show the seismic displacement time histories from Newmark analyses for both suites. Figures 9a and 9b show the displacements at the end of earthquake from FLAC and Newmark analyses for both suites. Figure 10 shows the earthquake and intensity parameters for both suites and the FLAC and Newmark displacements.
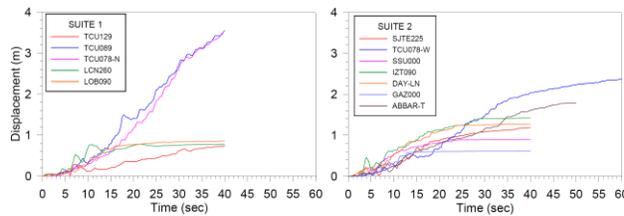
Figure 7a. FLAC displacements at the crest for Suite 1

Figure 7b. FLAC displacements at the crest for Suite 2
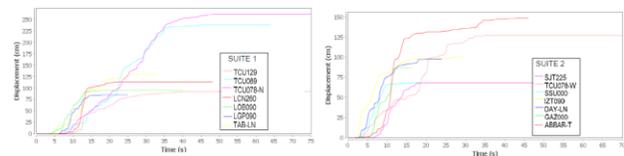
Figure 8a. Newmark displacements at the cerst for Suite 1

Figure 8b. Newmark displacements at the cerst for Suite 2
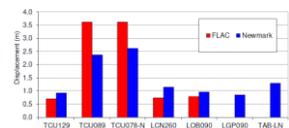
Figure 9a. FLAC and Newmark displacements at the cerst for Suite 1
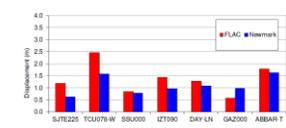
Figure 9b. FLAC and Newmark displacements at the cerst for Suite 2
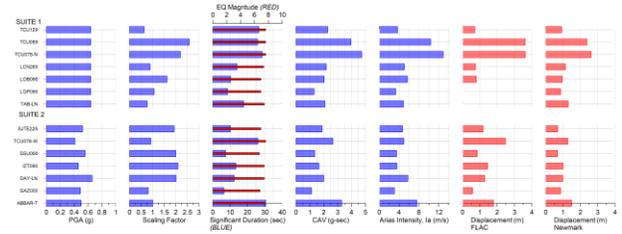
Figure 10. Earthquake intensity parameters and displacements for Suites 1 and 2

The predicted displacements by both FLAC and Newmark type analyses are sensitive to the input record in Suite 1 with relatively large displacements occurring for TCU078-N and TCU089 records. The maximum and average FLAC displacements predicted using Suite 1 are 3.6m and 1.9m respectively, with significant difference between maximum and average. However, the maximum and average displacements predicted using Suite 2 are 2.5m and 1.4m, respectively, which are smaller than those predicted by Suite 1. The standard deviation is also smaller in displacements predicted by Suite 2.

Although the Suite 1 was generated by matching the spectra instead of uniform scaling, they predicted generally greater and wider range of displacements than Suite 1. A key reason for this is the AI as shown in Figure 10. Greater scaling factors used for the two time histories TCU089 and TCU078-N resulted in greater AI, which apparently led to greater displacements by both FLAC and Newmark analyses highlighting the importance of scaling factor and the AI. It can also be seen that the displacements generally correlate well with the AI as shown in Figure 10. In the analyses conducted, there is a good correlation also between the simplified Newmark analyses and the more complex FLAC analyses indicating that the Newmark analyses, which are quick and easy to perform can be used to provide means of assessing the records before undertaking more complex and time consuming FEM or FDM analyses.

Another notable factor is that the Amax and CSR profiles did not show such large variation observed in displacements, indicating that they are relatively insensitive to the duration effect of the earthquake or the earthquake intensity parameters such as AI. SHAs do not provide AI for the target earthquake, which could be used for more objective selection of time histories representative of the design earthquake. This is partly due to lack of well-established correlations to reliably predict AI.

6.2 Example 2: Earthdam Analysis Using Scaled records

Seismic response of a 50 m high earthfill dam located in interior BC far away from the Cascadia subduction zone was assessed using a suite of six earthquake records. The 10,000 year return period seismic hazard at the dam site is dominated by the local crustal earthquakes with over 90% of the hazard coming from shallow crustal earthquakes. The suite of six records was selected from five earthquakes with magnitude ranging between M6.3 and M6.8. The

records were uniformly scaled so that the average spectra of the six records approximately matched the target spectra within the period range of interest for the dam, which was taken as 0.5s-2s. The target spectra was taken as the 10,000 year return period UHRS with a PGA of 0.46 g. The scenario earthquake was defined as an M6.7 earthquake occurring at 12 km distance from the dam site.

Estimated representative ranges: PGA: 0.34-0.57 g ; AI: 1.0-2.5m/s; Significant Duration: 7-14 sec. Parameters of selected records are: Scaling factor: 0.6-1.5; AI: 1.3-2.2m/s; Significant duration: 7-11 sec. These parameters generally fall within the estimated ranges.

Similar to Example 1, two types of analyses were performed: (1) FLAC analyses using an effectives stress based constitutive model to capture liquefaction and cyclic softening of soils; and (2) Newmark rigid sliding block analyses. In the selection of records, the AI and significant duration were considered.

Figures 11 and 12 show the records and the target and spectra of the selected and scaled records, respectively. Figure 12 also shows the average spectra of the six records after scaling. Note that the records were not matched to the target spectra. Figure 13 shows the earthquake and intensity parameters and the displacements predicted using FLAC and Newmark type of analyses. Despite the consideration of the key earthquake and intensity parameters including AI during the selection, the FLAC predicted much greater displacements for the first two records (EQ1 and EQ2) compared to THE other four records as shown in Figures 13 and 14. Such large discrepancy was not evident in the displacements predicted by the Newmark type of analyses. The APPARENT reason for this is the discrepancy between the target spectra and the spectra of these two records evident in Figure 12.
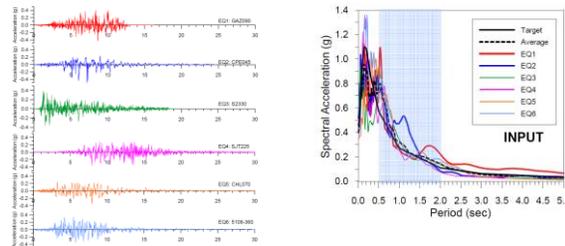
Figure 11. Earthquake   Figure 12. Spectra
Records
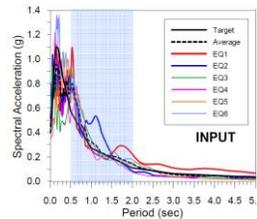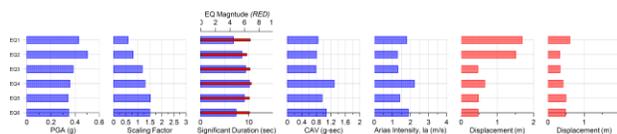
Figure 13. Earthquake intensity parameters of records

The surface spectra corresponding to ground motions at the dam crest were obtained from ground response analyses and shown in Figure 15, which shows greater amplification of ground motions for the first two records compared to others. Note that the FLAC analyses can capture any amplification of ground motion but not the

Newmark type of analyses, which uses a rigid body sliding block model and cannot capture any amplification.
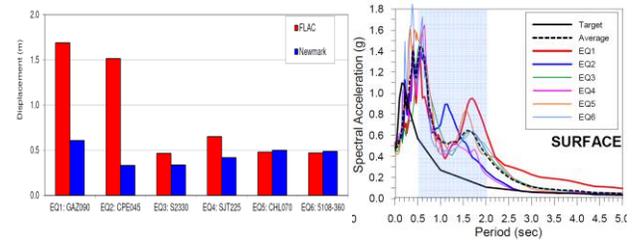
Figure 14. FLAC and NewmarkFigure 15. Spectra at the displacements at the end ofcrest surface of the dam earthquake

The analyses highlight the importance of closely matching the target spectra during uniform scaling especially around the natural period of the structure being analysed. Any large discrepancy may not become evident in Newmark type of analyses but will become evident in more detailed numerical analyses, which normally treat the dam as flexible body and capture any amplification effect.

6.3   Example 3: Analysis of a Bridge Site Using Records from Three Distinct Sources Matched to the UHRS

Seismic performance of a bridge located approximately 100 km east of Vancouver, Canada was assessed using a suite of records under a 2,475 year return period earthquake with firm ground PGA of 0.21 g. Thirteen records from past earthquakes were selected and modified to match the targets spectra in time domain using the computer program Ez-Frisk (2007). Ground response and Newmark type of deformation analyses were conducted to study the influence of records. Guidelines by Tremblay et al. (2015) were generally followed.

The seismic hazard at the bridge site arises from three sources: (1) local crustal earthquakes occurring on the North American Plate; (2) deep in-slab earthquakes occurring on the subducting Juan de Fuca plate; and (3) Cascadia subduction interface earthquakes occurring at the interface between the subducting Juan de Fuca plate and the North American plate. The hazard contributions from the three sources at the bridge site for the period range of interest, which was taken as 0.3s to 0.5s are: Crustal: 55%; In-slab: 30% and Interface: 15%. The representative scenario earthquakes for the three sources are: Local crustal: M7 R40; In-slab: M7.3 R125; Interface: M8.5 R190 where R is the distance. The contributions and scenario earthquakes were identified from seismic de-aggregation analysis results.

The target spectra, earthquake magnitude, site Vs30, PGA, PGV, PGD, AI and CAV were considered during the records selection. The suites consist of six records representing crustal, four records representing in-slab and three records representing the interface earthquakes. The records were taken from five crustal earthquakes with M7-7.3, four in-slab earthquakes with M6.7-7.2 and three subduction earthquakes with M8-9.

The subduction interface source appears to dominate the hazard at the site for period above 2s. However, the fundamental period of the generally stiff overburden soils

at the bridge site is less than 2s and hence not influenced by the long duration subduction interface earthquake. The time histories representing all three sources of earthquakes were either scaled or modified to match the UHRS, although the scenario spectra corresponding to the three sources would be different.

Figures 16 and 17 show the time histories and the target and spectra of the matched records, respectively. Figure 18 shows the various earthquake and intensity parameters for the matched records. Figure 18 clearly shows that the AI, significant duration and CAV for the interface records from M8-M9 earthquakes are much greater than those for the crustal and in-slab records.
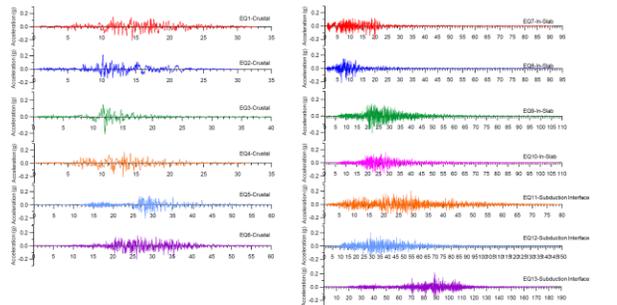
Figure 16. Earthquake records representing the three sources
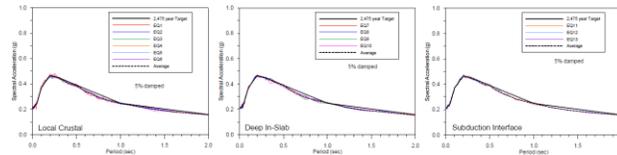
Figure 17. Spectra of the records representing three sources
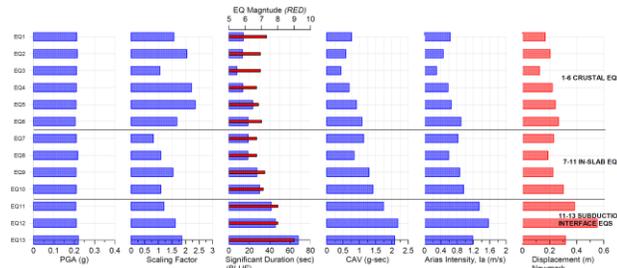
Figure 18. Earthquake intensity parameters and Newmark displacements for the records represneting three sources

Amax and CSR profiles from ground response analyses conducted for a pier at the south riverbank are shown in Figure 19a and 19b, respectively. The range of Amax and CSR generally fall within a narrow band and the weighted average of responses from all three sources (i.e. for all 13 records) generally agree with the individual averages corresponding to the records from the three sources. In the computation of weighted average, 0.55, 0.30 and 0.15 were assigned to crustal, in-slab and interface earthquakes, respectively and they correspond to the hazard contribution from the three sources. It indicates that the Amax and CSR are relatively insensitive to the records

representing three distinct sources when all the records are matched to the same UHRS.

The surface spectra for the ground surface at the south riverbank were developed from the ground response analyses using all the 13 records and shown in Figure 20. As shown, the records representing the three different sources did not result in any significant difference on the spectra of the surface motions. Figures 20 also shows that the surface motion spectra are also relatively insensitive to the records representing three distinct sources.
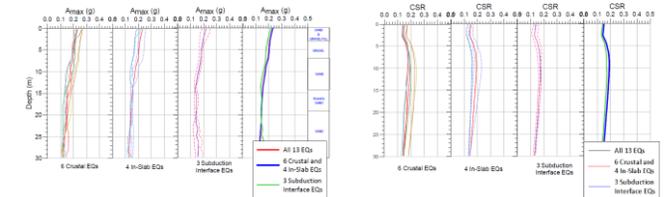
Figure 19a. Amax profiles   Figure 19b. CSR profiles
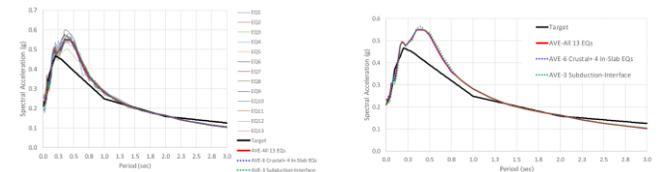
Figure 20. Comparison of surface spectra

A Newmark sliding block analysis was conducted using all 13 records for a yield acceleration of 0.03 g and the results are shown in Figures 18 and 21. The seismic displacements are sensitive to the records and the average displacements predicted by the crustal, in-slab and interface records are 0.20 m, 0.24m and 0.42m, respectively. Figure 21 illustrates that, unlike Amax, CSR or the surface spectra, the displacements predicted using the interface records are much greater if they are scaled to the UHRS. The trends in the displacements appears to correlate well with the AI, significant duration and CAV.
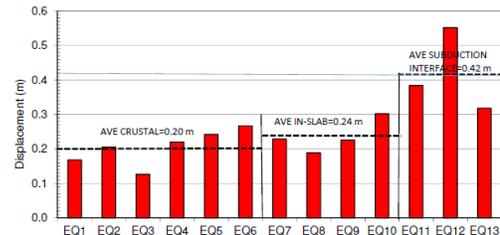
Figure 21. Newmark displacements from records representing the three sources

6.4   Example 4: Analysis of a Bridge Site Using Records from Three Distinct Sources Matched to the Scenario Spectra

Seismic performance of a bridge located approximately 20 km southeast of Vancouver, Canada was assessed under 475 year return period earthquake with firm ground PGA of

0.21 g. A suite of fifteen records representative of 475 year return period earthquake was used in the assessment.

The bridge is located in a seismically active area in the Cascadia subduction zone within the North American Plate close to the plate boundary between the subducting Juan de Fuca plate and the North American Plate. The tectonic setting around the bridge site is shown in Figure 22. The seismic hazard at the bridge site arises from the same three sources that influenced the bridge in Example 3. However, as this bridge is located much closer than the bridge in Example 3 to the Cascadia subduction zone, the influence of subduction interface and in-slab earthquakes are greater.

The seismic de-aggregation analyses results showed that within the period range of interest, which was taken as 0.5-2s for the bridge, the mean magnitude varies between M7.2-7.7. However, the modal magnitude is M7 at 0.5-1s, and at 2s, it increases to M9. The hazard contributions from the three sources are shown in Table 1 and in Figure 23. The hazard up to 0.5s period is dominated by the in-slab earthquakes (> 65%), and when the hazard from crustal and in-slab are combined they dominate up to 2s period. Beyond, 2s, the interface earthquake dominates with 64% of hazard coming from this type of earthquake at 5s.

The following scenario earthquakes were selected to represent the three sources: (1) Local crustal: M6.5R24; in-slab: M7.5R100; and interface: M8.5R130. The response spectra for these scenario earthquakes were computed using the GMPEs used by Geological Survey of Canada to develop the 2015NBCC seismic hazard maps. The shapes of the spectra corresponding to the three sources are different. The scaled response spectra corresponding to the scenario earthquakes are shown with the target spectra in Figure 24. The spectral shape of the scenario crustal earthquake (M6.5, R24) is similar to the UHRS up to 0.5 sec, and the shape of in-slab scenario earthquake is similar between 0.5-2.0 sec. The shape of interface scenario earthquake (M8.5, R130) is similar to UHRS beyond 2.0 sec. Also, the spectral shape of the interface earthquake is significantly different from that of the crustal or in-slab earthquake. In cognizant of this fact, in the development of time histories, two target spectra were considered: one for crustal and in-slab and another for the subduction interface. These two target spectra are shown in Figure 25 which was used as scenario spectra in the selection, scaling and matching time histories corresponding to the three sources of earthquakes.

Figure 22. Tectonic setting around the site
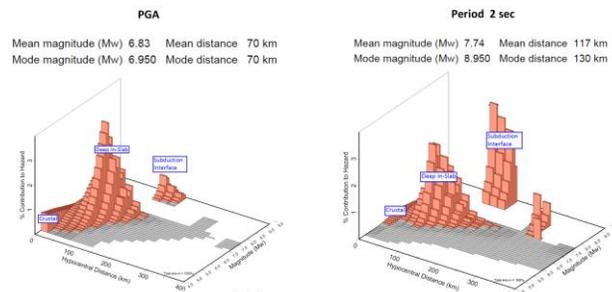
Figure 23. De-aggregation results at PGA and 2s
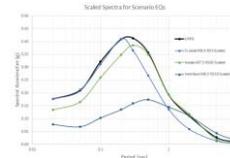
Figure 24. Scaled scenario earthquake spectra for the three sources
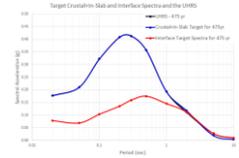
Figure 25. Scaled spectra representing crustal+in-slab and interface earthquakes

The target scenario spectra shown in Figure 25, earthquake magnitude, site Vs30, PGA, PGV, PGD, AI and CAV were considered during the records selection. A suite consists of five records representing each of the three sources (crustal, in-slab and interface) were selected. The records were taken from five crustal earthquakes with M6.6-7.1, four in-slab earthquakes with M6.1-7.6 and five subduction earthquakes with M8-9.

Figures 26 show the time histories. Figure 27 shows the various earthquake and intensity parameters for the matched records. Since a different spectrum was used for the interface earthquake, the AI, and CAV for the interface records are not very different from those for the crustal and in-slab records except for the EQ14 record from the M9 Tohoku earthquake, which had a total duration of about 300 seconds.

Table 1. Hazard Contributions from the three sources

Period (sec)	Acc (g)	Crustal	In-Slab	Interface	Crustal + In-Slab
0.01	0.176	28%	59%	13%	87%
0.2	0.406	24%	66%	9%	91%
0.3	0.410	19%	68%	12%	88%
0.5	0.355	16%	67%	17%	83%
1.0	0.192	18%	52%	30%	70%
2.0	0.111	11%	48%	41%	59%
5.0	0.027	19%	17%	64%	36%
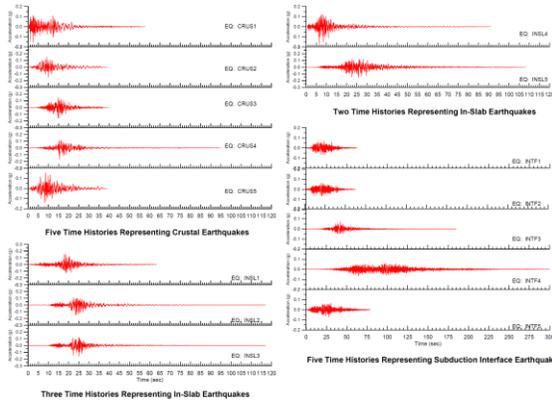
Figure 26. Earthquake records representing the three sources

Amax and CSR profiles from ground response analyses conducted for a pier near the south riverbank are shown in Figure 28. The range of Amax and CSR generally fall within a narrow band for each source. However, the average Amax and CSR of the interface records are generally lower than the average of the combined crustal and in-slab records. The difference compared to the results in Example 3 can be attributed to the use of a different spectrum for the interface earthquake (See Figure 25) with lower amplitudes up to 2s period than the UHRS. The estimated natural period of the ground is less than 2 sec.
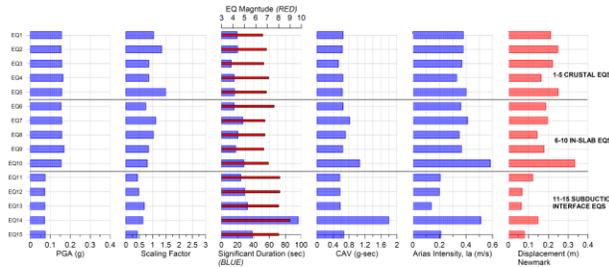
Figure 27. Earthquake intensity parameters and Newmark displacements for the records representing three sources

The surface spectra for the ground near the south riverbank were developed from the ground response analyses using all the 15 records. Figure 29 shows the comparison of the average spectra for the interface records and the average spectra for the combined crustal and in-slab records. The two spectra are different with interface spectra being generally lower up to about 2.5s and then it becomes slightly greater.
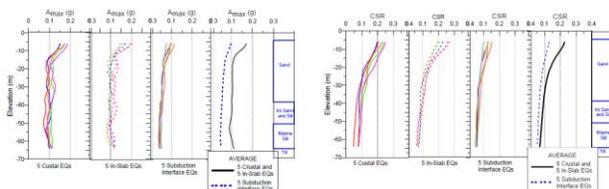
Figure 28. Amax and CSR profiles developed using records representing three sources
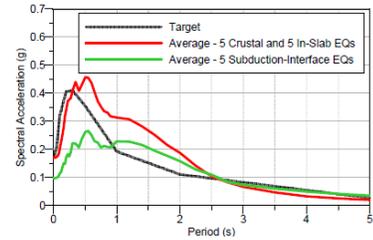
Figure 29. Comparison of surface spectra
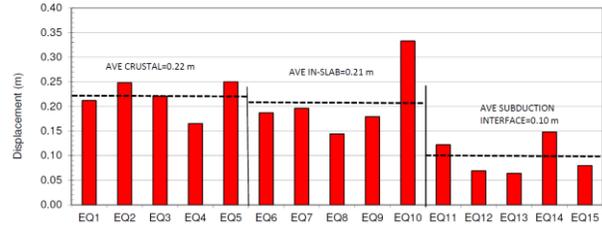
Figure 30. Newmark displacements from records representing the three sources

A Newmark sliding block analysis was conducted using all 15 records for a yield acceleration of 0.03 g, and the results are shown in Figure 27 and Figure 30. Unlike in Example 3, the seismic displacements predicted by the interface records are much smaller than the displacements from the crustal and in-slab records. The average displacements predicted by crustal, in-slab and interface records are 0.22m, 0.21m and 0.10m, respectively. Note that the fundamental period of the ground in this example bridge is less than 2s, which falls outside the range dominated by the interface earthquakes. In this case, the Amax, CSR and seismic displacements also show similar trend.

7   COMMENTS

SHA normally stops at providing the geometric mean of the UHRS using a probabilistic based approach. The UHRS does not represent a particular scenario earthquake but can be considered as an envelope of several sources contributing to the hazard. The use of CMS is becoming increasingly popular with practitioners, especially when more than one source with distinct characteristics dominates the hazard within the period range of interest. Whether UHRS or multiple CMS/scenario earthquake spectra is adopted, they do not fully describe an earthquake record or represent earthquake shaking. Other intensity parameters such as AI, significant duration, CAV are also important. However, most of the GMPEs are limited to developing spectra only and a very few GMPEs or empirical correlations are available to compute these intensity parameters or to assess aleatory uncertainties in them. Their direct use within the probabilistic framework of SHA is also not normally done.

A key issue with the use of intensity parameters to select records is that there is no single intensity measure which can be used as efficient and sufficient predictor to capture all the effects which are important in geotechnical engineering. AI, CAV, spectral acceleration at 1 or 1.5 times the fundamental period of structure, VSI (integral spectral velocity over 0.1-2.5s) and PGV are some of the

key measures (Kramer, 2009). Their applicability varies for example depending on the stiffness or fundamental period of structure, type of structure or failure mode (i.e. pile yielding during earthquake or settlement of shallow foundations) etc. Therefore, to capture potential epistemic and aleatory uncertainties, multiple intensity measures should be considered during record selection and the suite should have adequate number of records.

Recognizing that the acceleration spectra does not fully capture the earthquake shaking and there are other intensity measures that may be important, a method called generalized conditional intensity measure approach (GCIM) was used by Bradley (2010) and Peterman and Rathje (2017), which appears a potential solution but has not been adopted widely by the practitioners.

While records are continuously added to the databases, selection records under following conditions has been a challenge: (1) Sites in low seismic areas such as in Eastern and Central North America where there have not been many historical records; (2) Sites close to the subduction zone as mega subduction interface type earthquakes are rare and the subduction deep in-slab earthquakes are also infrequent; (3) The low probability (5,000 and 10,000 year return period) events represent rare event and it is difficult to find representative earthquakes in the data base; and (4) records from representative hard rock conditions.

8 A PROCEDURE FOR SELECTION AND SCALING OF RECORDS FOR GEOTECHNICAL ANALYSES

As noted, typically two broad cases of geotechnical analyses are performed that will requires earthquake records.

Case 1: Ground response analyses to assess the amplification/deamplification of ground motions, develop design spectra, and earthquake induced cyclic stress ratio (CSR) which are used in liquefaction or strain softening assessment of soils. These analyses are typically 1D and performed using total stress based equivalent linear method embedded in the computer program SHAKE or variations of it.

Case 2: Seismic deformation and seismic soil-structure interaction analyses using complex constitutive models capturing the nonlinear, hysteretic, liquefaction/cyclic softening characteristics of soils under the FEM or FDM (i.e. FLAC) based computer programs.

Steps involved in a simple and procedure that can readily be adopted with the information that can be obtained without any elaborate analyses or assessment for or most sites in Western Canada is described below.

1. Estimate the potential range period of interest for the ground/geotechnical structure. Consider softening of ground/structure during shaking and lengthening of the period. Also capture the key modes if more than one mode of vibration is important.
2. Assess where the ground motions are proposed to be applied for the Case 1 and Case2 type analyses and assess its Vs30. Usually the firm ground or bedrock beneath the structure governs.

3. Obtain the UHRS from SHA. Perform de-aggregation analyses to identify key sources dominating the hazard within the period range of interest and their percentage contributions. Define scenario earthquake(s) representing each source that dominates hazard as M-R pairs. Develop deterministic spectra for each scenario earthquake and compare their spectral shape to the UHRS. Assess whether UHRS can continue to be used for record selection and scaling, or development and suite of CMS or scenario spectra for each dominating source are required. (Note if a site specific seismic hazard assessment is performed, the UHRS corresponding to each dominating source at the same probability level can be obtained and their shapes can be compared). At the end of this step, either a single UHRS or multiple (typically between two or three) CMS/Scenario spectra are selected.
4. Calculate the range of earthquake intensity parameters for the scenario earthquakes, defined as a pair of M-R using empirical correlations. Consider Arias intensity, significant duration, CAV, PGA, PGV, PGD. Estimate both median and 84th percentile ranges and adopt higher confidence level for critical structures, with low probability design earthquakes. Give priority for Arias intensity, significant duration and CAV over other intensity parameters.
5. Define how many records are to be used to represent UHRS or the CMS/Scenario spectra. Depending on the complexity of site and project, select between 7 and 11 records.
6. Select earthquake records from database for each scenario earthquake. Define spectra during selection but also define ranges for M, R, mechanism, Vs30, PGA, AI, Significant duration and CAV. Check the matching of records when scaled uniformly using factor between 0.5-2.0. Define broader range for intensity parameters during this first step and select two to three times the actual number of records required. Conduct screening of the records by narrowing down the amount of deviation from spectra (i.e. avoid large peaks and troughs within the period range of interest), scaling factor and other key intensity parameters namely M, AI, significant duration and CAV. Broader range can be adopted for other parameters.
7. Use of uniformly scaled records is preferred for critical structures with low probability design earthquakes. However, ensure that the average of the spectra agrees well with the target spectra and there are no large peaks and troughs within the period range of interest. Records modified to match the target spectra can be used for structures with return period 2475 year or less. Use time domain matching procedure (i.e. Abrahamson, 1992).
8. Prior to undertaking any complex or detailed analyses using FEM or FDM, screen the records by conducting the Newmark type of analyses. i.e.

Conduct analyses for a range of potential yield accelerations. If any anomaly is observed with some records, investigate and remove them from the suite.

9. Recalculate the earthquake and intensity parameters of selected records including average, standard deviation, maximum, minimum etc to ensure that they fall well within the estimated range.

The same procedure could be adopted for sites outside Western Canada provided that adequate number of natural records for the design earthquake is available in the database.

9 SUMMARY AND CONCLUSIONS

With increased reliance on performance-based design, geotechnical seismic assessments are performed using earthquake records. Available design codes and guidelines do not provide adequate guidance for the selection scaling of time histories. A brief overview of the methods that are used in current practice is presented, highlighting the challenges faced by the geotechnical practitioners. Examples of ground response and seismic deformation analyses of earth dams and bridges are presented to highlight some of the issues, and to emphasize the importance of considering some of the key earthquake and intensity parameters, which included: Identification of scenario earthquakes representing seismic hazard, if it arises from distinct sources with different spectral shape and amplitude; scaling factors; Arias intensity; and significant duration. The impact of ignoring some of the earthquake and intensity parameters on the following types of geotechnical analyses are also presented: ground response, Newmark type sliding block analyses and seismic deformation analyses using FLAC capturing the nonlinear, hysteretic and liquefaction/strain softening behaviour. A simple procedure for practitioners is also recommended for the selection and scaling of records for geotechnical seismic analyses.

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