DISPLACEMENT-HAZARD ANALYSIS OF EARTHEN DAMS

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Abstract

The current standard-of-practice for evaluating the seismic performance of earth dams is to develop an elastic acceleration response spectrum based on a hazard design level (or return period), which is then used as an input to estimate engineering demand parameters. The issue with this approach is that it assumes the hazard design level for an intensity measure (e.g. spectral acceleration) is consistent with the hazard design level for the engineering demand parameter of interest, which may not always be appropriate. In this paper, we present an approach for the performance-based assessment of earth dams that relies on a hazard-consistent estimation of seismically induced displacements. The proposed approach relies on the conditional scenario spectra (CSS) framework to select input ground motions that directly reproduce the probabilistic seismic hazard analysis (PSHA) results at the site of interest. The output of this framework results in a set of earthquake time series each with an assigned scale factor and rate of occurrence. This allows for the estimation of seismically induced displacement hazard curves that can directly relate displacement with a design hazard level.

The proposed approach is applied to an earth dam located in the Vancouver, Canada region, where both shallow crustal and subduction earthquakes contribute significantly to the ground-motion hazard. Displacement hazard curves estimated with the proposed approach are used to evaluate alternative simplified approaches including: (1) deformation results from standard-of-practice procedures of selecting a limited number of input ground motions (typically 7 or 11) based on spectral acceleration hazard (typical PSHA approach); and (2) develop hazard curves for ground-motion intensity measures (IMs) other than just spectral acceleration (e.g. Arias Intensity) to calculate a weighted average displacement based on the contribution to the IM hazard for each source type. We found that the simplified approach (2) produced displacement results that are more consistent with those estimated directly from displacement hazard curves.

Keywords: seismic hazard; earth structures; displacement hazard analysis; conditional scenario spectra

1. Introduction

The current standard-of-practice for seismic performance assessment of earth dams is to develop an elastic acceleration response spectrum based on a hazard design level (or return period), then use ground motions based on this hazard level as an input to estimate engineering demand parameters (EDPs). The issue with this approach is that it assumes the design hazard level for an intensity measure (e.g. spectral acceleration) is consistent with the design hazard level for the EDP of interest (e.g. seismically induced slope displacement), which may not always be appropriate. This assumption can be particularly problematic when evaluating earth structures, especially those affected by ground motions from different tectonic environments (e.g. shallow crustal and subduction earthquakes). Under this scenario, dynamic analyses using state-of-practice procedures may lead to high variability in the earth structure's response, which makes selection of an appropriate design value for the EDP of interest quite challenging.

This paper discusses the performance-based assessment of earth dams, considering a hazard-consistent estimation of seismically induced displacements. The hazard-consistent estimation of displacements relies on the conditional scenario spectra (CSS) framework to select input ground motions that reproduce the probabilistic seismic hazard analysis (PSHA) results at the site of interest (e.g. spectral acceleration hazard curves), which results in a set of earthquake time series each with an assigned scale factor and rate of occurrence. This allows for the estimation of seismically induced displacement hazard curves that can directly relate displacement with a design hazard level.

To demonstrate the application of the hazard-consistent procedures, this paper illustrates their application for a fictitious earth dam located in the Vancouver, Canada region, where both shallow crustal and subduction earthquakes contribute significantly to the spectral acceleration (Sa) hazard. Displacement hazard curves are used to evaluate alternative simplified approaches including: (1) simplified methods that use the deformation results from the standard-of-practice methodology of selecting a limited number of input ground motions (typically 7 or 11) based on Sa hazard, designated as the standard PSHA approach; and (2) more advanced methods that develop hazard curves for ground-motion intensity measures (IMs) other than just Sa (e.g. Arias Intensity) and calculate a weighted average displacement based on the contribution to the IM hazard for each source type.

Section 2 of this paper presents procedures that rely on state-of-practice approaches, section 3 discusses a procedure based on Arias intensity (I_A) hazard curves, section 4 presents the estimation of displacements using displacement hazard curves, which is the approach used as the basis for comparisons in this paper, and section 5 shows a comparison between different approaches.

2. Standard PSHA Approach

2.1 Analysis Overview

A common approach to evaluate the seismic performance of an earth dam involves selecting input ground motions based on the uniform hazard spectrum (UHS) to compute the dynamic response of the structure. A traditional PSHA was performed for a fictitious earth dam located in the Vancouver, Canada region, where both shallow crustal and subduction zone events were considered in the analysis. The earth dam is approximately 15 m in height with an average shear wave velocity of about 235 m/s.

The PSHA was performed using version 3 of the HAZ45 program [1] and the BC Hydro seismic source model [2]. The NGA-West2 ground-motion models (GMMs) [3, 4, 5, 6, 7] were used for shallow crustal sources and the relationships by Abrahamson, et al. [8, 9] were used for subduction zone sources. The ground-motion hazard curves are presented in Fig. (1).

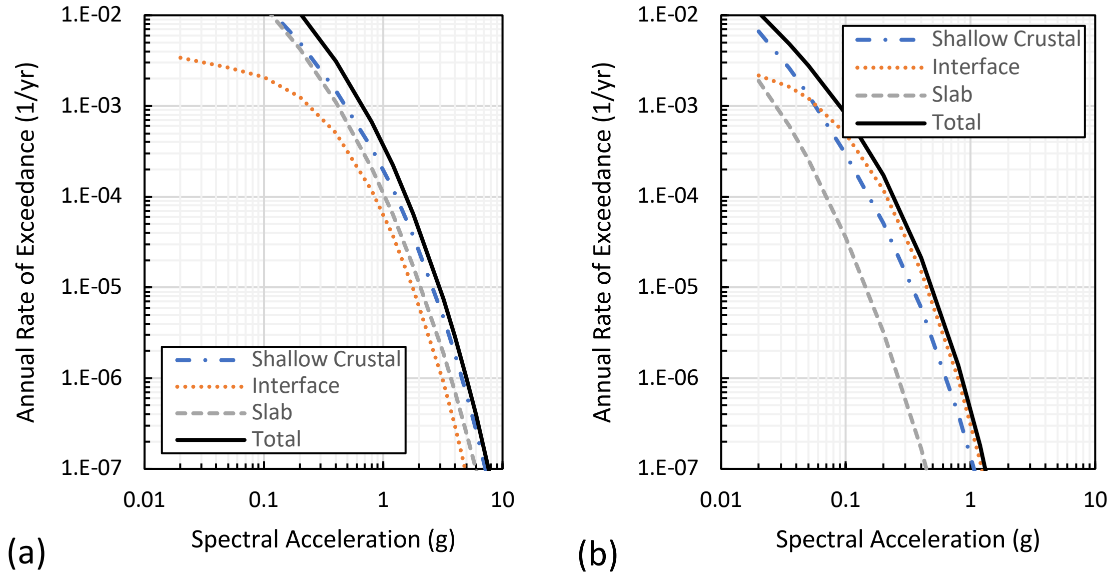

Fig. 1 – Ground-motion hazard curves for the fictitious earth dam: (a) T = 0.2 seconds; (b) T = 2.0 seconds

The hazard results were subsequently deaggregated to determine the scenarios with the highest contribution to the Sa hazard, the results of which are presented in Table 1. The UHS corresponding to a 10^{-4} hazard level (10,000-year return period) was then broken into two conditional mean spectra (CMS) for each source type [10, 11]. The CMS were conditioned on the 10,000-year UHS at periods of 0.2 and 2.0 seconds. Eleven sets of horizontal component time histories were scaled to the CMS for each source type at each conditioning period, resulting in a total of 66 sets of earthquake time series for the displacement analysis.

Table 1 – Deaggregation results by source type

Source Type	**Period (sec)**	**Contribution to *Sa* Hazard (10,000-yr RP)**	**Moment Magnitude (M_W)**	**Rupture Distance (km)**
Shallow Crustal	0.2	0.57	6.5	15
Interface		0.16	9.0	140
Intra-Slab		0.27	6.8	80
Shallow Crustal	2.0	0.29	6.9	16
Interface		0.69	9.0	140
Intra-Slab		0.01	7.1	80

The selected 66 ground motions were used to estimate seismically induced displacement in the earth dam. For this purpose, the simplified model proposed by Hale [12] was employed. This model uses a transfer function to estimate the response of the potential sliding mass of the dam caused by input ground motions, then estimates displacement using a Newmark sliding block analysis. The displacement results for each source type are presented in Table 2.

Table 2 – Displacement results for the standard PSHA approach using 66 ground motions

Source Type	T_0 (sec)	Median Displacement (cm)	Standard Deviation of Displacement (ln units)
Shallow Crustal	0.2	13	0.8
Interface		60	1.7
Intra-Slab		5	1.2
Shallow Crustal	2.0	17	1.0
Interface		13	1.5
Intra-Slab		21	1.5

2.2 Displacement results for the seismic performance assessment

Due to the high variability of the displacement results (5 to 60 cm), determining which value to use for the stability assessment of the earth dam remains a non-trivial task. Four potential options of selecting a displacement value to use in the stability assessment are presented in the following sections.

2.2.1 Option 1 – Largest Value

This option simply considers the largest value of deformation regardless of source type. This is the most conservative approach and the simplest to use in that it requires no further calculations. Even though the earthquake time histories were selected and scaled based on the CMS for each source type, each CMS was conditioned on the UHS for the total hazard; therefore, simply using the largest displacement regardless of source type implicitly assumes that the Sa hazard from the individual source type is equal to the total Sa hazard. This will likely result in a displacement value that is overly conservative.

Using this option, the resulting displacement would be approximately 60 cm associated with the interface tectonic setting. It should be noted that there is a significant difference between this displacement value and that of the other source types, but the contribution of interface events to Sa hazard at this conditioning period is only about 16 percent.

2.2.2 Option 2 – Weighted average using Sa hazard deaggregation weights

In this option, the design displacement is estimated as a weighted average displacement with weights based on the deaggregation of Sa hazard. This is a less conservative approach compared to option 1 and will generally produce reasonable results when the average displacement for each source type is consistent with their contribution to the Sa hazard (e.g. sources with large contributions cause large displacements). This approach, however, will be unconservative when a source produces a large displacement but has a low contribution to the Sa hazard.

Using the contribution of each source type to Sa hazard presented in Table 1 and the displacement values presented in Table 2, the weighted average displacement values are 18 and 14 cm for CMS conditioned at periods of 0.2 and 2.0 seconds, respectively. Selecting the larger value between the two condition periods results in a displacement of 18 cm to be used in the stability assessment of the fictitious earth dam.

2.2.3 Option 3 – Hazard by Source

This option considers the hazard evaluation by source type and the construction of three separate UHS. The CMS for each source type will each be conditioned on a reduced value of Sa (rather than the UHS for total hazard) and the displacement is re-evaluated using a new set of ground motions. This approach will result in reasonable displacement values when one source type produces much higher displacement values than the other sources and/or the dynamic response of the structure from the other source types is negligible.

To avoid additional dynamic analyses, the displacement values presented in Table 2 were scaled down by the ratio of Sa from each individual source type (10,000-year return period) to the Sa from the total hazard. The largest, scaled-down value of displacement for the fictitious earth dam is approximately 33cm corresponding to an interface event and a conditioning period of 0.2 seconds.

2.2.4 Option 4 – Largest displacement value between options 2 and 3

The fourth option is to estimate displacements using both options 2 and 3, then select the largest of the two values for the stability analysis. This is an attempt to obtain a value that is not overly conservative (e.g. option 1), and at the same time accounts for factors that may not be considered in either option 2 or option 3. Option 4 results in a displacement value of 33 cm (option 3).

3. Arias Intensity Hazard Approach

An alternative approach that extends beyond the standard PSHA approach without running a full displacement-hazard analysis is to compute hazard for a second ground-motion IM that correlates well with the EDP of interest. In the case of seismically induced displacements, I_A is an efficient parameter [13]; hence, it will be considered. In this approach, the design displacement value is estimated as a weighted average displacement, with weights based on the deaggregation of the additional IM hazard. This should result in a reasonable displacement value if the contribution of each source type to the additional IM hazard is similar to the contribution to displacement hazard.

For the fictitious earth dam, I_A hazard curves were developed using HAZ45 [1], as well as relationships proposed by Abrahamson, et al. [14] and Macedo, et al. [15] for shallow crustal and subduction zone sources, respectively. Fig. (2) presents the developed I_A hazard curves. Using the I_A deaggregation weights for each source type associated with a 10,000-year return period, the new weighed average displacement values for conditioning periods of 0.2 and 2.0 seconds are approximately 42 and 15 cm, respectively. Selecting the larger of the two values, this alternative approach results in a displacement value of 42 cm for the fictitious earth dam.

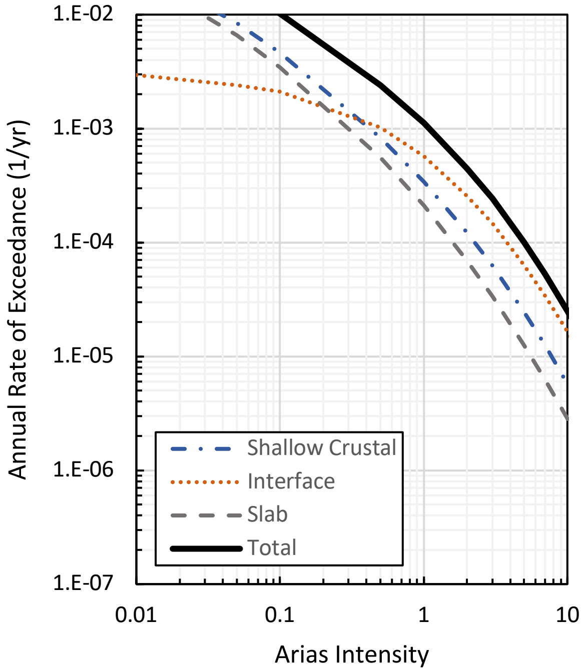

Fig. 2 – Arias Intensity hazard curves by source type for the fictitious earth dam

4. Displacement Hazard Approach

To evaluate each of the simplified methods discussed in the previous sections, displacement hazard curves were directly computed from a set of earthquake time series developed for a range of Sa hazard levels. The CSS approach presented by Arteta and Abrahamson [16] was used to develop of suite of earthquake time histories, each with a rate of occurrence such that the hazard for Sa and I_A were recovered. For the fictitious earth dam, two sets of CSS were developed using the CSS program by Linda Al Atik [17]: one for a conditioning period of 0.2 seconds and a second set conditioned at 2.0 seconds. Although only one conditioning period is required for this approach, a second conditioning period was added to check the sensitivity of the displacement hazard results to the selected conditioning period.

To compute the displacement hazard for the ficitious earth dam, a total of 1552, 1854, and 1793 sets of time series were selected and scaled based on a conditioning period of 0.2 seconds for shallow crustal, interface, and intra-slab earthquakes, respectively. For a conditioning period of 2.0 seconds, a total of 1586, 1729, and 1212 sets of time series were selected and scaled for shallow crustal, interface, and intra-slab events, respectively. The UHS recovered by the CSS for each source type over 14 hazard levels are presented on Fig. (3). The hazard levels ranged from $2x10^{-3}$ to 10^{-7} in order to adequately capture the hazard level of interest, which is 10^{-4} (10,000-year return period). The I_A hazard curves captured by the CSS for both conditioning periods are presented on Fig. (4).

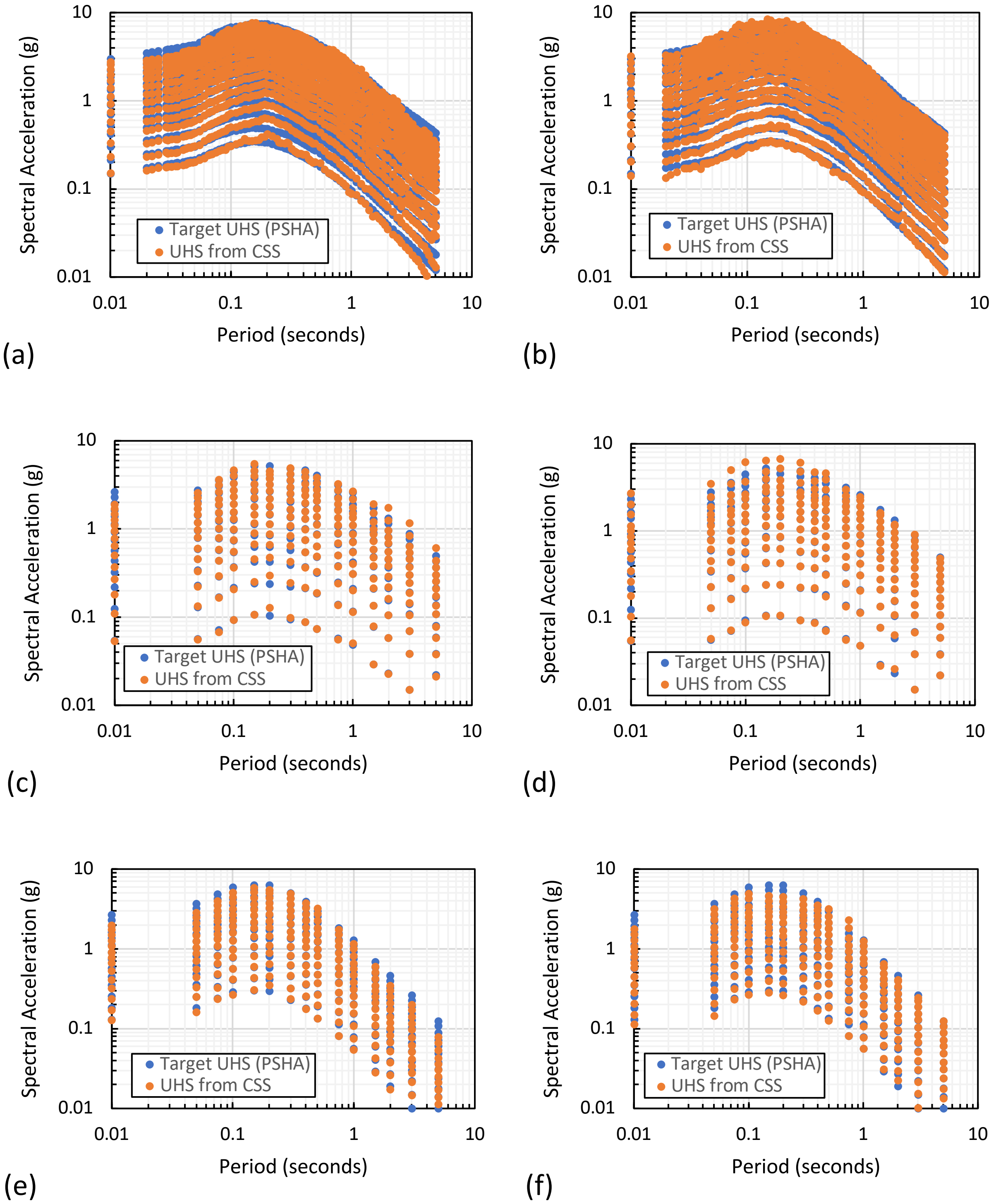

Fig. 3 – Uniform hazard spectra computed from the CSS compared with the target UHS from the PSHA for: (a) shallow crustal, T_0 = 0.2 seconds; (b) shallow crustal, T_0 = 2.0 seconds; (c) interface, T_0 = 0.2 seconds; (d) interface, T_0 = 2.0 seconds; (e) intra-slab, T_0 = 0.2 seconds; (f) intra-slab, T_0 = 2.0 seconds.

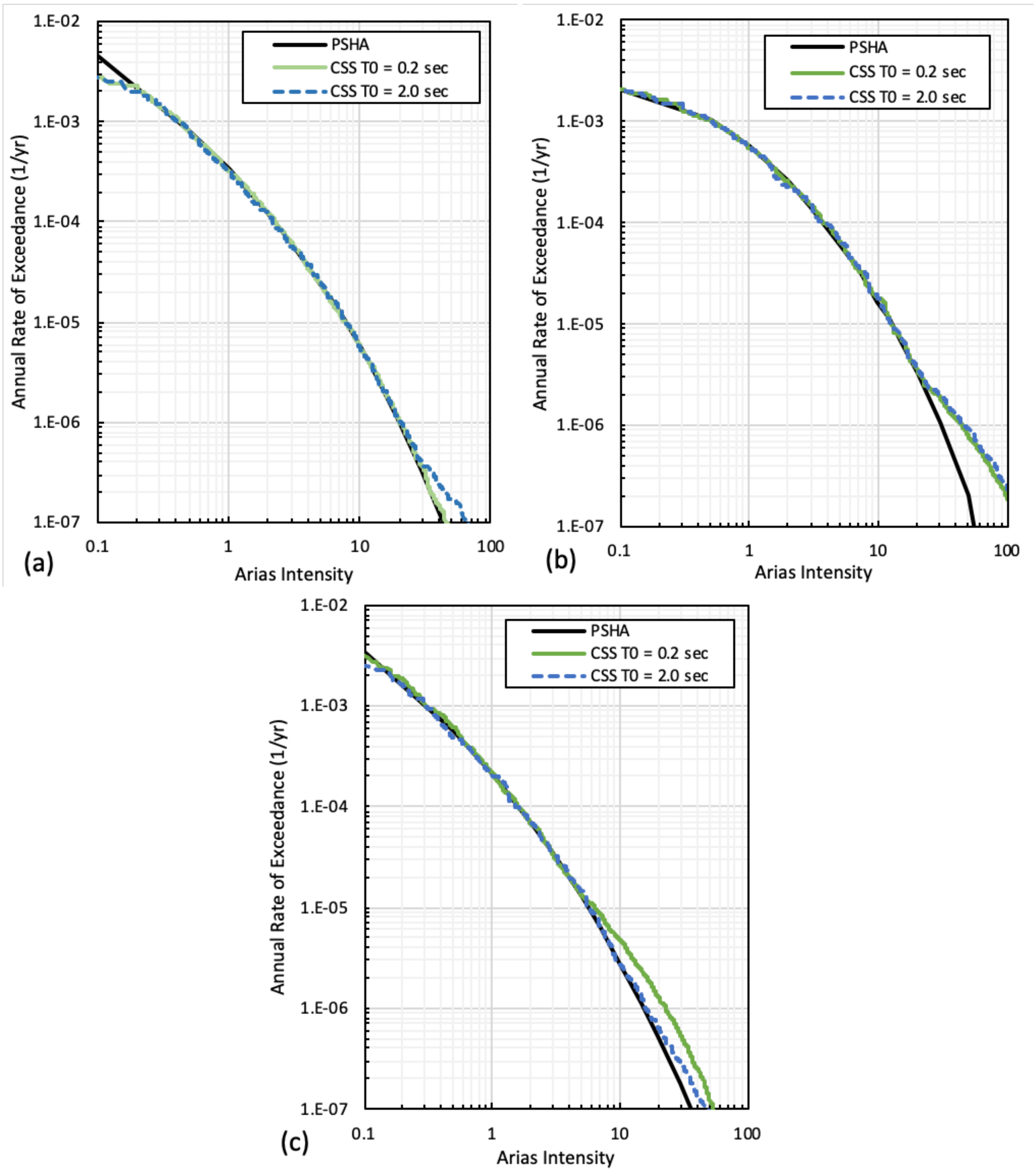

Fig. 4 – Arias Intensity hazard computed from the CSS conditioned at 0.2 and 2.0 seconds compared with the target hazard curves from the PSHA for: (a) shallow crustal; (b) interface; and (c) intra-slab events.

The simplified displacement model by Hale [12] was used to estimate displacements resulting from each acceleration time history. The displacement associated with each time history in combination with the associated rate of occurrence was then used to construct displacement-hazard curves for the dam being evaluated. The displacement-hazard curves are presented on Fig. (5).

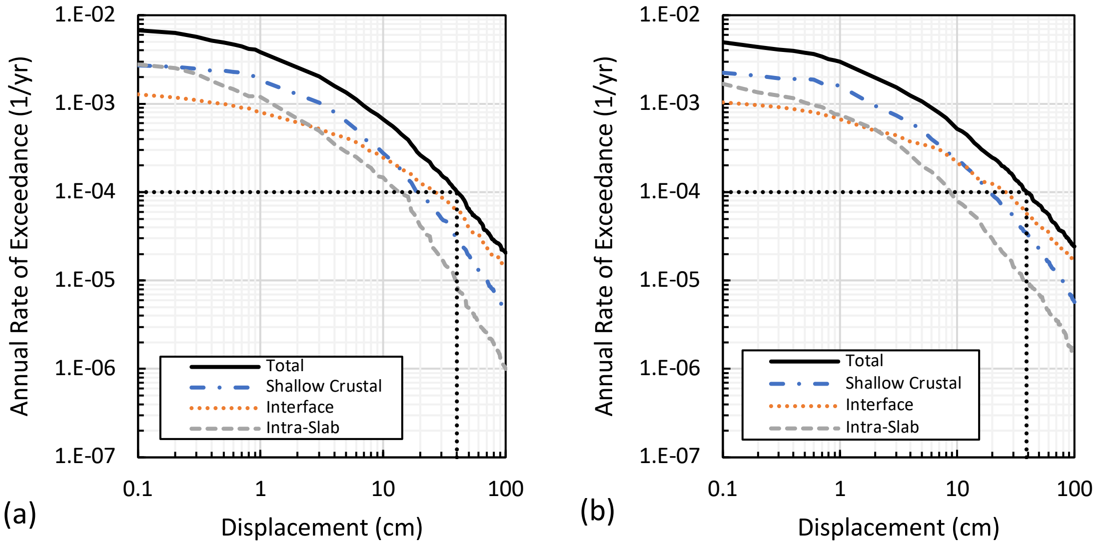

Fig. 5 – Displacement-hazard curves constructed from CSS conditioned at a period of: (a) 0.2 seconds; (b) 2.0 seconds.

Using the hazard curves in Fig (5), the displacements associated with a 10,000-year return period are approximately 40 and 39 cm for conditioning periods of 0.2 and 2.0 seconds, respectively. This indicates the displacement-hazard curves are not sensitive to the selection of conditioning period for development of the CSS.

5. Comparison of Results

The displacement results from each of the simplified methods discussed in section 1 (e.g. options 1 to 4), the weighting scheme based on the I_A hazard deaggregation, and the displacement hazard curves associated with a 10,000-year return period are presented in Table 3. Fig. (6) also presents a graphical comparison of the displacement results for each procedure.

Table 3 – Displacement results from each approach

Approach	**Option**	**Displacement (cm)**	**Description**
1	1	60	Largest displacement
1	2	18	Weighted average from *Sa*-hazard deagg weights
1	3	33	Hazard by source
1	4	33	Largest of options 2 and 3
2	--	42	Weighted average from I_A-hazard deagg weights
3	--	40	Displacement-hazard curves from CSS (10,000-year RP)

As previously mentioned, approach 1 corresponds to state-of-practice procedures and approach 2 considers a weighting scheme based on the I_A hazard. Approach 3 relies on the estimation of displacement hazard curves.

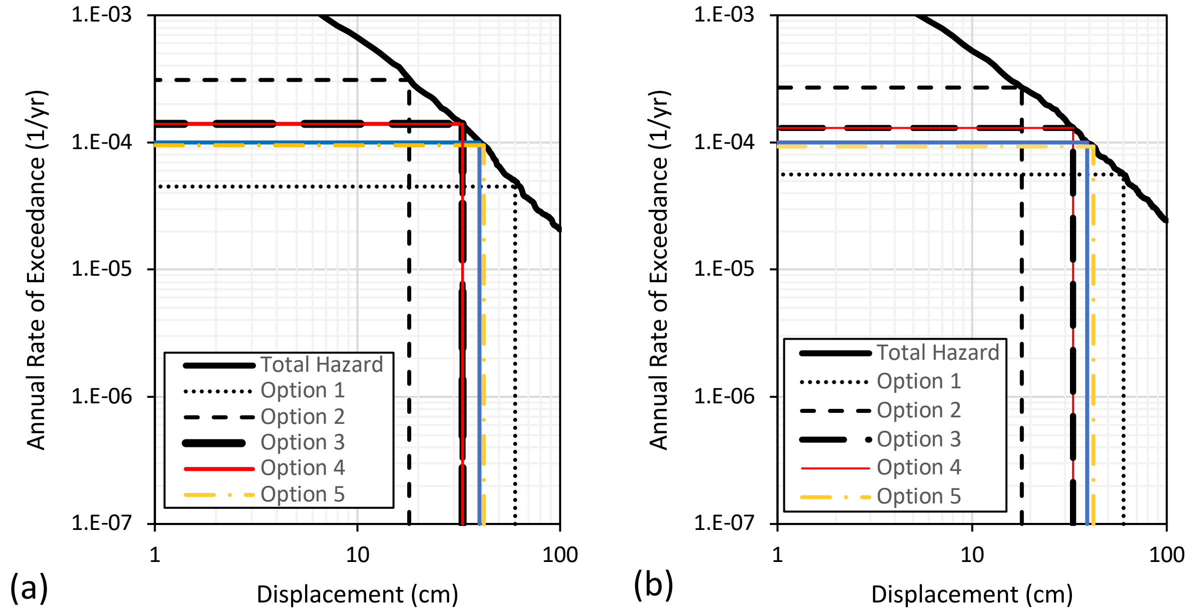

Fig. 6 – Displacement results comparison for the two general approaches using the displacement-hazard curves computed from the CSS conditioned at a period of: (a) 0.2 seconds; (b) 2.0 seconds. The data plotted as option 5 corresponds to the weighted average displacement based on I_A hazard (approach 2).

6. Discussion and Conclusion

This paper presents a comparison of three general approaches to select a design displacement value for the seismic evaluation of earth dams that are affected by ground motions from multiple tectonic settings. These approaches are: (1) state-of-practice, based on Sa hazard; (2) weighted average based on I_A hazard; and (3) displacement hazard, which is considered the more robust approach. The metric of comparison used in this paper consists of displacement-hazard curves computed directly from earthquake time histories developed using the CSS approach.

The displacement estimates using state-of-practice procedures may have large variability. In the example discussed in this paper, the range of displacements varied from approximately 5 to 60 cm, where the lowest estimate corresponds to an intra-slab tectonic setting and the largest to an interface tectonic setting. This large range of estimates associated with different tectonic settings makes the selection of a representative displacement design value challenging. Hence, four options to select an appropriate displacement value have been proposed and evaluated. Option 4 (e.g. the largest between options 2 and 3) provided the closest estimate to the displacement hazard curve estimate. However, this estimate is unconservative (e.g. 32 cm versus displacement-hazard curve estimate of 40 cm).

Approach (2) for I_A hazard produced displacement results that are more consistent with those estimated directly from the displacement hazard curves. This is due to the shape of the hazard curves (or contribution of each source type to hazard) for I_A, which are similar to the displacement-hazard curves. This is demonstrated on Fig. (7) where a similar pattern in the contribution of individual I_A and displacement-hazard curves to the total hazard is observed.

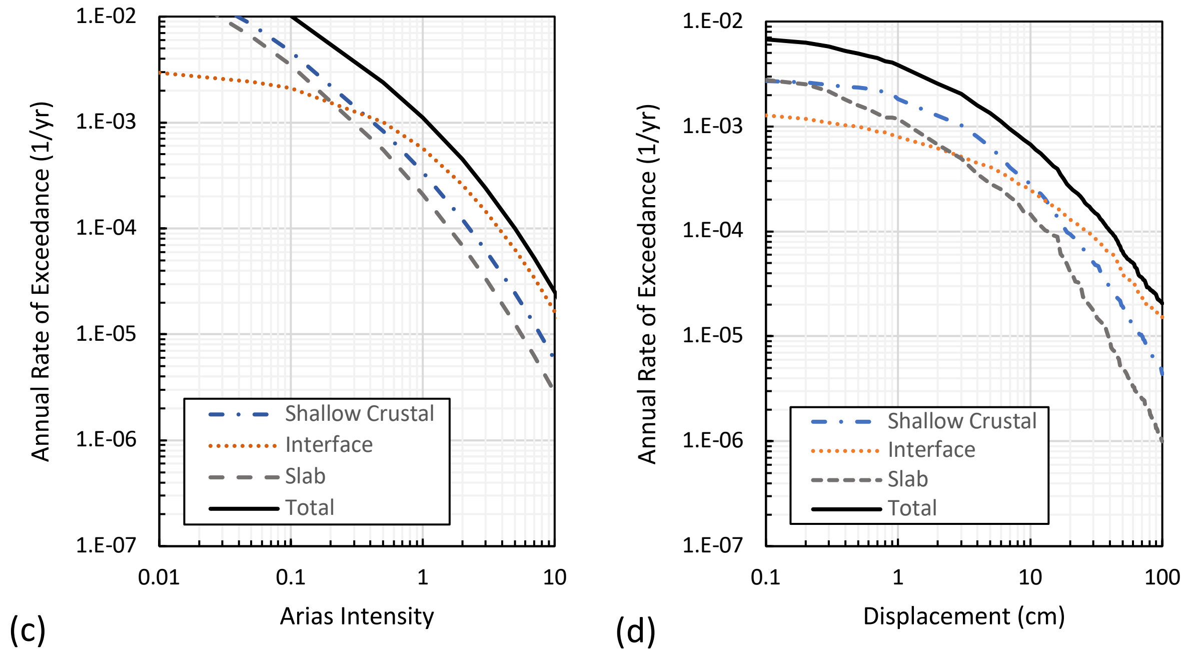

Fig. 7 – Hazard curves comparison for: (a) Arias Intensity; and (b) slope displacement from CSS conditioned at $T_0 = 0.2$ seconds.

Approach (3), which involves constructing EDP hazard curves, is considered to be the most complete solution; however, it is currently not practical for most projects due the large computational cost involved in performing hundreds of dynamic analyses with a large set of input ground motions. Based on the results of this study, including hazard curves for I_A or another IM that takes into account earthquake duration (e.g. cumulative absolute velocity) may provide more insight than hazard for Sa alone when assessing the seismic stability of earth structures near sources from different tectonic environments.

6. References

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