



EXPLORING THE USE OF “M9” GROUND MOTION SIMULATIONS FOR SEISMIC RISK ASSESSMENT OF DAMS

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Abstract

The Willamette Valley is located in the state of Oregon in the United States of America. It is in a relatively active seismic region and contains numerous high-hazard dams that are located upstream of relatively large population centers. The seismic hazard within the Willamette Valley is heavily influenced by magnitude 9 earthquakes on the Cascadia subduction zone. The potential life-loss consequences associated with dam failure justify considering very rare ground motions when evaluating the structural response of the dam. Response history analysis is the preferred method for the U.S. Army Corps of Engineers when determining if modifications need to be made from a dam safety perspective. The number of historical ground motion records from large subduction zone earthquakes is relatively small. The number of historical records relevant to the rare ground motions that need to be considered is even less, and currently there are no such records from the Cascadia subduction zone. Typically, records are selected based on how well they fit a target response spectrum, ignoring other intensity measures and allowing significant scaling of the historical records. Consideration of intensity measures such as Arias intensity can help determine how appropriate such scaled ground motions are. Trying to target other intensity measures when selecting records, however, only reduces the number of relevant records even further. Consideration of U.S. Geological Survey ground motion simulations from the University of Washington “M9” project could expand on the pool of ground motions from which to select.

This paper compares how well historical ground motions and M9 simulations fit target spectra within the Willamette Valley, as well as the expected Arias intensities, both of which have been seen to strongly influence the structural response of dams. The expected Arias intensities are calculated for a location within the Willamette Valley using conditional ground motion models that estimate Arias intensity from a target spectrum. The Arias intensity for the historical and M9 ground motion records that were selected and scaled to match conditional mean spectrum targets are calculated and compared to the expected Arias intensities. Observations are made on the extent to which the M9 simulations would be a reasonable means of increasing the number of ground motions from which to select, based on how they compare to scaled historical records. Those observations indicate that inclusions of some simulated records within a suite used to evaluate the structural response of a dam can be beneficial.

Keywords: ground motion selection; M9 simulations; structural response of dams; Arias intensity; subduction zone



1. Background

Several dams are exposed to high seismic hazard within the Willamette Valley. The Willamette Valley is located in the state of Oregon in the United States of America. Fig. 1 shows the location of the Willamette Valley in dark green. Many of these dams were constructed prior to 1970, and seismic considerations were either minimal or nonexistent. The relatively high seismic hazard in the Willamette Valley is influenced by the Cascadia subduction zone (CSZ), which is capable of producing magnitude 9 earthquakes. Several population centers within the Willamette Valley exceed 50,000 people and are located in the inundation zone if any of these dams were to fail. Several of the dams also have small communities located within a couple of miles downstream, which would also experience significant inundation. This combination creates the potential for sizeable life safety risk, which necessitates protecting against even very rare earthquake ground motions. In some cases, the magnitude of potential life loss from a dam failure warrants considering earthquake ground motions with return periods of 10,000 and even 100,000.



Fig. 1 - Location of Willamette Valley (area in green), modified from U.S. Army Corps of Engineers [1]

Three main sources produce seismic hazard within the Willamette Valley: interface and intraslab subduction zone events as well as crustal events. Recent probabilistic seismic hazard analyses (PSHAs) have indicated that the seismic hazard at dams owned and operated by the U.S. Army Corps of Engineers (USACE) within the Willamette Valley is dominated by interface subduction zone events along the CSZ.

Never has a magnitude 9 earthquake been recorded on the CSZ and only a few have been around the world with close-in recordings. This limits the number of historical ground motion records that could be used within a response history analysis of USACE dams. When selecting records that are representative of seismic events of interest, target spectral acceleration plots have typically been generated based on relevant ground motion prediction equations. Historical records are then selected for use with a finite element model based on how well they matched the target spectrum. In many cases, the records have to be scaled up and, in some cases, spectral matching is necessary in order to better match the target.

Previous finite element analyses have shown a correlation between non-linear dam response and Arias intensity, even after matching the ground motion records to a target spectrum. Historically, Arias intensity has not been considered by USACE when selecting records to use within a finite element analysis. With the use of non-linear finite element analysis increasing and the correlation between dam response and Arias intensity suggests that this approach should change. The current USACE approach to response history analysis is to run a reasonably large suite of ground motion records whose average matches each target spectrum, in an effort to determine the expected response of the structure. Already a limited number of records from magnitude 9 subduction zone events makes it difficult to collect a reasonably large suite of records. Consideration of other intensity measures such as Arias intensity would only further reduce the number of records that could be considered representative.

Magnitude 9 earthquakes on the CSZ have been simulated by the U.S. Geological Survey (USGS) as part of the University of Washington "M9" project. This paper compares the ground motions from those



simulations against historical records from recent magnitude 9 subduction zone earthquakes and evaluates whether the simulations could be used to broaden the pool of records from which to choose for finite element analyses.

2. Seismic Hazard

The first step in this evaluation was to establish target spectral accelerations against which ground motions could be compared. Target spectral accelerations were created as part of a 2017 PSHA [2] for six USACE projects within the Willamette Valley. Uniform Hazard Spectrum was created for the 2,475-year return period and Conditional Mean Spectrum (CMS) for the 9,950- and 100,000-year return periods. CMS was created for both short (0.2-seconds) and long (1-second) spectral periods. The long period spectra for one of those projects are the focus of this study. The focus on the long-period targets is because recent finite element analysis for concrete dams within the Willamette Valley have indicated that certain historical records from the 2011 Tohoku earthquake matched to the long-period CMS targets for 9,950- and 100,000-year return periods result in significantly greater responses compared to other historical records. This paper tries to put these records as well as other records from magnitude 9 subduction zone earthquakes into context with simulated records. The conditioning bands for the long period were broadened to be between 0.5 and 2.0 seconds.

Past finite element analyses have indicated that typically USACE dams within the Willamette Valley would be expected to experience minimal damage during earthquakes with return periods shorter than 2,475 years. As noted previously, the potential consequences from failure of USACE dams within this region are large. Therefore, the focus of this study was on the seismic hazard associated with return periods 2,475, 9,950, and 100,000 years, with a larger emphasis on the 9,950- and 100,000-year return periods. Fig. 2 shows the target spectral accelerations for the dam considered in this study.

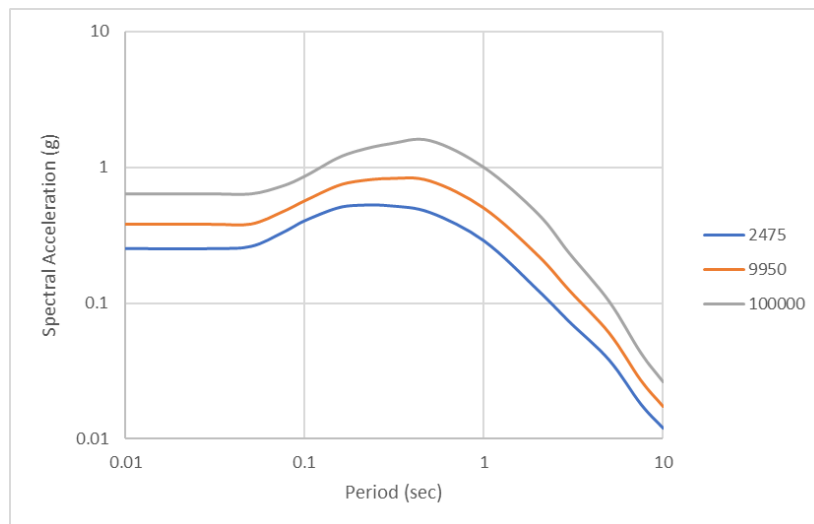


Fig. 2 – Target Spectra for 2,475-, 9,950-, and 100,000-Year Return Periods

In order to consider Arias intensity within ground motion selection, the Arias intensity for every record under consideration had to be calculated as well as an Arias intensity target. Arias intensity is defined by Eq. (1) [3] with $a(t)$ being the acceleration at time t and t_{\max} being the end of the time history..

$$I_A = \frac{\pi}{2g} \int_0^{t_{\max}} a(t)^2 dt \quad (1)$$

The Arias intensity target was calculated using a conditional ground motion model for subduction zones established by Macedo et al. [4]. The equation for the Arias intensity target is defined by Eq. (2), where I_A



and V_{S30} are in m/s, M_w is the moment magnitude of the event and peak ground acceleration (PGA) and 1.0 second spectral acceleration (SA1) are in fractions of g.

$$\ln[I_A] = c_1 \ln(V_{S30}) + c_3 M_w + c_4 \ln(PGA) + c_5 \ln(SA1) \quad (2)$$

Macedo et al. [4] established region-specific coefficients for Japan, Taiwan, South America, and New Zealand, as well as coefficients representative of all regions. Since the CSZ is not located within any of the specific regions, the all-region coefficients were used for this study. Macedo et al. also established separate coefficients for interface and intraslab events. Since recent PSHAs have shown that the seismic hazard for USACE dams in the Willamette Valley is dominated by interface events, only the interface coefficients were used. Those coefficients are detailed in Table 1.

Table 1 – Coefficients of the Macedo et al. [4] Arias Intensity Ground Motion Model Used

Coefficients					
All Regions	c_1	c_2	c_3	c_4	c_5
Interface	0.85	-0.36	0.53	1.54	0.17

The calculated median Arias intensity targets for the dam considered in this study are shown in Table 2.

Table 2 – Arias Intensity Targets

Return Period (years)	M_w	PGA (g)	SA 1 (g)	V_{S30} (m/s)	Arias Intensity (m/s)
2,475	8.8	0.00	0.25	760	2.21
9,950	8.8	0.00	0.38	760	4.58
100,000	8.8	0.00	0.64	760	11.40

3. Historical Ground Motion Records

When it comes to magnitude 9 subduction zone earthquake events, not many historical ground motion records exist, and none have occurred along the CSZ. The two most recent events are the 2010 M_w 8.8 Maule earthquake that occurred off the coast of Chile and the 2011 M_w 9.1 Tohoku earthquake that occurred off the coast of Japan. These two events were the basis for selecting historical records both in the recent USACE hazard report for the Willamette Valley [2] and in this paper. As part of the USACE PSHA done in 2017 [2], five three-component records were selected to match CMS targets [5] for both short and long spectral periods and for various return periods. The focus of this study is on the horizontal ground motion so only the two horizontal components were utilized. These five two-component records along with additional historical records were pulled from the Tohoku and Maule events [6] that were within the distance to rupture and shear-wave velocity (V_{S30}) ranges that defined the CMS targets. These ranges are 65 to 250 km for rupture distance and 330 to 1,100 m/s for V_{S30} . This resulted in 30 two-component records from Tohoku and 13 two-component records from Maule, which include those selected as part of the 2017 PSHA [2].

As was the case with the USACE report, here each record was amplitude scaled to match each specific CMS target. The scale factor for each record was selected to minimize the sum of square errors (SSE) from Jayaram et al. [7]. Eq. (3) calculates the SSE between the natural log of the spectral acceleration at period T_j of the scaled record, $\ln S_a(T_j)$, and the natural log of the spectral acceleration of the target, $\ln S_a^{(s)}(T_j)$, over the number of periods considered, p . In this study, 118 periods between 0.33 and 3 seconds are considered, consistent with the long-period range used in the USACE hazard report for the Willamette Valley [2].

$$SSE = \sum_{j=1}^p [\ln S_a(T_j) - \ln S_a^{(s)}(T_j)]^2 \quad (3)$$

Once the scale factor was calculated for each record, the Arias intensity of each scaled record was also calculated using Eq. (1). The variation in Arias intensity ($I_{A \text{ diff}}$) between each scaled record and the target was calculated in an effort to compare how well they matched using Eq. 4, where I_{Ac} is the calculated Arias intensity



in m/s for each record and I_{At} is the target Arias intensity in m/s. $I_{A \text{ diff}}$ is a percent difference that is reported as a decimal for this paper. So, a value of 0.5 indicates the calculated Arias intensity is 50% greater than the target, a value of 1.0 means double, 2.0 triple and so on.

$$I_{A \text{ diff}} = \frac{I_{Ac} - I_{At}}{I_{At}} \quad (4)$$

4. M9 Simulations

Simulated ground motion records generated by the USGS as part of the University of Washington “M9” project [8][9] are used here as a comparison with historical records. The ground motions from the M9 project included three-component records at a site near the dam considered in this study for 30 earthquake realizations that vary both the stochastic and physically simulated portions. All of the simulated records were associated with a magnitude 9 earthquake and a V_{S30} of 600 m/s. The distance to rupture for each realization varied from 97 to 165 km with a geometric mean of 131 km. For comparison, the range for distance to rupture for the 2011 Tohoku event is 68 to 226 km with a geometric mean of 121 km, and V_{S30} between 332 and 930 m/s. The range for distance for the 2010 Maule event is 65 to 176 km with a geometric mean of 110 km, and V_{S30} between 345 and 821 m/s. The simulated records were scaled here in the same manner as the historical records from Tohoku and Maule. The Arias intensities were also calculated in the same manner.

Before scaling, the spectral accelerations and the Arias intensities of the simulated records were compared with those of the Tohoku and Maule records, as shown in Fig. 3 and Table 3. On average, the spectral amplitude and Arias intensity of the simulated records is comparable to that of the Tohoku records, which can be attributed to similar distances to the respective ruptures. The spectral shape of the simulated records, however, is more similar to that of the Maule records, up to a period of 5 seconds where the spectral accelerations of the simulated records are relatively high. The average (geometric mean) Arias intensity for the Maule records, however, is significantly higher than the simulations, as shown in Table 3. When considering the spectral amplitude, spectral shape and Arias intensities of the simulated records, they are different compared to the Tohoku and Maule records. Of course, only the simulated records are specific to the CSZ. Whether this is why they differ could be informed by comparisons of simulations of the Tohoku and Maule earthquakes with the historical records. If the comparisons show good agreement, one could attribute the differences of the CSZ simulations to regional effects.

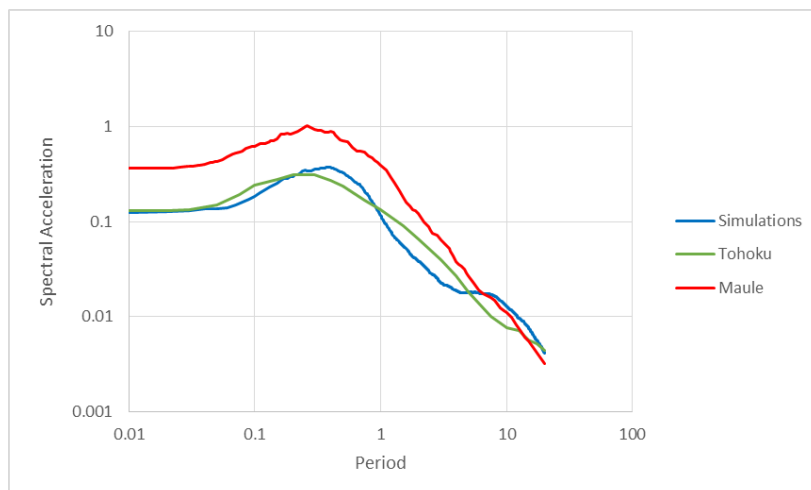


Fig. 3 – Geometric Mean Spectral Accelerations across Records



Table 3 – Geometric Mean Arias Intensity across Records

Seismic Event	Number of Two-Component Records	Geometric Mean Arias Intensity (m/s)
Simulations	30	0.6
Maule	13	4.5
Tohoku	30	0.95

5. Comparison of Historical Records to the Hazard Targets

The SSE for the spectral accelerations was plotted against $I_{A \text{ diff}}$. Fig. 4 shows the comparison for the records selected and scaled up to match the 9,950-year CMS target. The records for Maule and Tohoku are separated by color. Fig. 5 shows the comparison for the records matched to the 100,000-year CMS target.

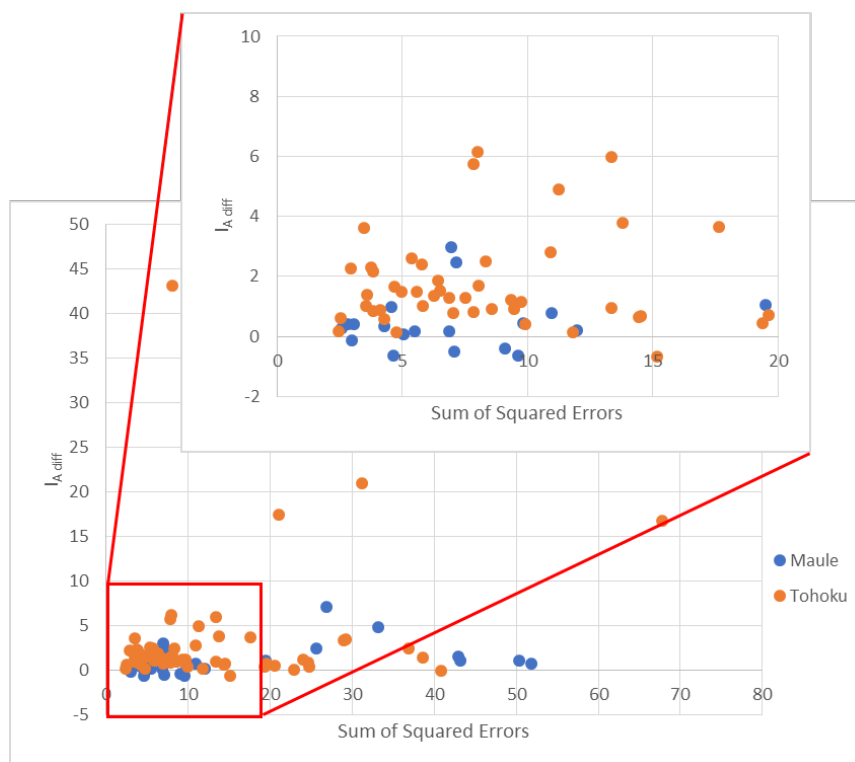


Fig. 4 – Comparison of Historical Records for 9,950-Year Return Period

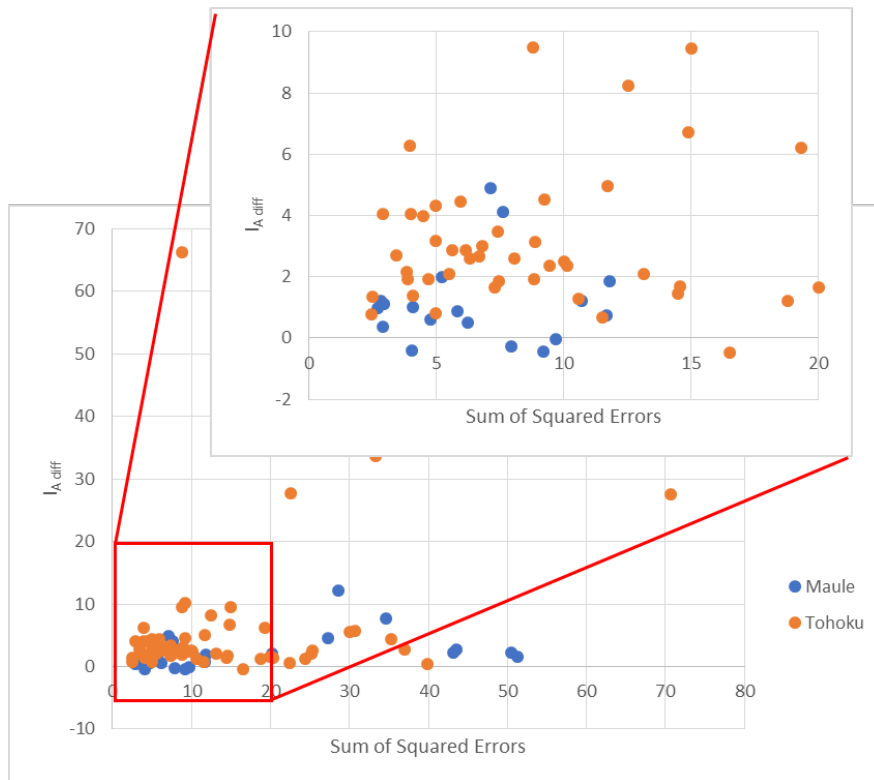


Fig. 5 – Comparison of Historical Records for 100,000-Year Return Period

As can be seen from Fig. 4 and Fig. 5, how well the historical records match the targets ranges widely. Table 4 compares how well the historical records match the spectral acceleration targets across return periods while Table 5 does the same for Arias intensity. For the spectral acceleration comparison, the mean noted is the arithmetic mean of the SSE while the variation for the mean in the Arias intensity comparison is the difference between the geometric mean Arias intensity of the records to the target divided by the target Arias intensity.

Table 4 – Comparison of Spectral Acceleration Sum of Squared Errors (SSE)

	Return Periods (years)		
	2,475	9,950	100,000
Range	2 to 64	2 to 68	2 to 70
Mean	14	14	14
90% Range	3 to 42	3 to 42	3 to 42

Table 5 – Comparison of $I_{A \text{ diff}}$ for Historical Records

	Return Periods (years)		
	2,475	9,950	100,000
Range	-0.78 to 28.55	-0.67 to 43.18	-0.47 to 66.27
Mean	0.59	1.29	2.54
90% Range	-0.54 to 4.83	-0.33 to 6.90	0.08 to 11.63

Looking at the spectral acceleration comparison, the range of SSE does not vary much with return period, neither does the mean or the range in which 90% of the SSE data fall. The variation in the Arias intensity, however, increases and the ranges get larger with increasing return period. For each return period, the majority of the Arias intensity data is above the target, but there are a handful of records which fall below.



Both the upper and lower bounds for the Arias intensity comparison increase with increasing return period, but the upper bound increases to a much greater degree. The variation in the mean also increases with increasing return period. This shows that Arias intensity is disproportionately affected by scaling of the records only to spectral acceleration targets. Whereas the Arias intensity of the scaled records is increased by the square of the scale factor, per Table 1 and Eq. (2) it is expected to increase by only the $1.54+0.17=1.71$ power. Thus, the more the records are scaled, the greater the difference between their Arias intensities and the target is expected to be.

Between the Tohoku and Maule records for all return periods considered, the maximum and variation in the mean for Arias intensity is significant. Table 6 shows a similar comparison as Table 5, except the Tohoku and Maule records are separated.

Table 6 – Tohoku vs Maule $I_{A \text{ diff}}$ Comparison

	Return Periods (years)					
	2,475		9,950		100,000	
	Tohoku	Maule	Tohoku	Maule	Tohoku	Maule
Range	-0.77 to 28.55	-0.78 to 5.09	-0.67 to 43.18	-0.63 to 7.14	-0.47 to 66.27	-0.45 to 12.10
Mean	0.88	0.07	1.70	0.55	3.22	1.36
90% Range	-0.25 to 11.25	-0.72 to 2.47	0.12 to 16.82	-0.60 to 4.34	0.67 to 27.62	-0.37 to 7.04

The minimum values on the ranges (of percent difference in Arias intensity) are quite comparable between Maule and Tohoku. The greater dissimilarity is in the mean and upper bounds. Those for Tohoku are significantly higher than those for Maule. This is best highlighted by the fact that the range of the percent difference in Arias intensity for the Tohoku records at the 2,475-year return period is greater than the range for the Maule records at the 100,000-year return period. This is largely attributable to scale factors. At the 9,950-year return period, the average scale factor for the Tohoku records is approximately 4.5, while for the Maule records it is only 1.5. At the 100,000-year return period, the average scale factor for the Tohoku records is 8.8 while it is only 3 for Maule.

Overall, the Maule records seem to be better matches to the hazard targets than the Tohoku records. Approximately the same percentage of Tohoku and Maule records are reasonable matches to the spectral acceleration targets, but a greater percentage of Maule records are reasonable matches to the Arias intensity target. For the sake of this study, it is assumed that the threshold of a reasonable match for spectral acceleration is an SSE less than 20 and an Arias intensity between half and double (-0.5 and +1.0) the target. This acceptability criterion is purely for comparison purposes only and should not necessarily be used for a specific project when selecting records. Based on these criteria, between 70% and 80% of both the Tohoku and Maule records are reasonable matches for spectral acceleration, and there is not much variation with return period. For Arias intensity, however, approximately 80% of the Maule records are reasonable matches compared to 60% for the Tohoku, at the 2,475-year return period. The percentage of historical records that are reasonable matches for Arias intensity decreases with increasing return period, and the difference between the Maule and Tohoku records grows. At the 9,950-year return period, approximately 47% of all the historical records are reasonable matches to Arias intensity with those from Maule and Tohoku being about 65% and 40%, respectively. At 100,000 years, only about 20% of all the historical records are good matches to Arias intensity, with those from Maule and Tohoku being about 40% and 10%, respectively. This equates to 17 of the 86 total historical records being considered reasonable matches to the Arias intensity target at the 100,000-year return period. If both spectral acceleration and Arias intensity are considered, the number of records that are reasonable matches decreases to 15 out of 86 at 100,000 years. Table 7 shows how many records are considered reasonable matches to both the spectral acceleration and Arias intensity targets, as well as how many are Maule vs Tohoku records. It should be noted that this represents just the number of individual record components that are considered reasonable matches. This is not the number of two-component records (both horizontal directions), which would be fewer. Future work should consider both horizontal components in the record comparison.



Table 7 – Historical Records that are Reasonable Matches to the Spectral Acceleration and Arias Intensity Targets

Return Period (years)	Tohoku	Maule	Total
2,475	29	17	46
9,950	19	16	35
100,000	4	11	15

All of the historical records selected as part of the USACE PSHA for the Willamette Valley [2] are reasonable matches in terms of spectral acceleration. This is expected because they were selected based on how well they matched the spectral acceleration target. These records, however, are not necessarily the best matches. Numerous other historical records could be considered better matches to the spectral targets. Of the records that could be considered reasonable matches to the spectral target, how well they match the Arias intensity target ranges widely. This is true for both the records that were and were not selected as part of the PSHA [2]. More than half of the selected records have Arias intensities that are more than double the target at a return period of 9,950 years, and only two have an Arias intensity less than double the target at the 100,000-year return period. If Arias intensity were considered during record selection for the 2017 USACE PSHA [2], it is likely that the suite of records chosen would have been different.

6. Comparison of Simulated Records to the Hazard Targets

The spectral acceleration SSE and variation in Arias intensity is plotted in the same manner as above for the simulated records. Fig. 6 shows the comparison for the records selected and scaled up to match the 9,950-year spectral target while Fig.7 shows the comparison for 100,000 years.

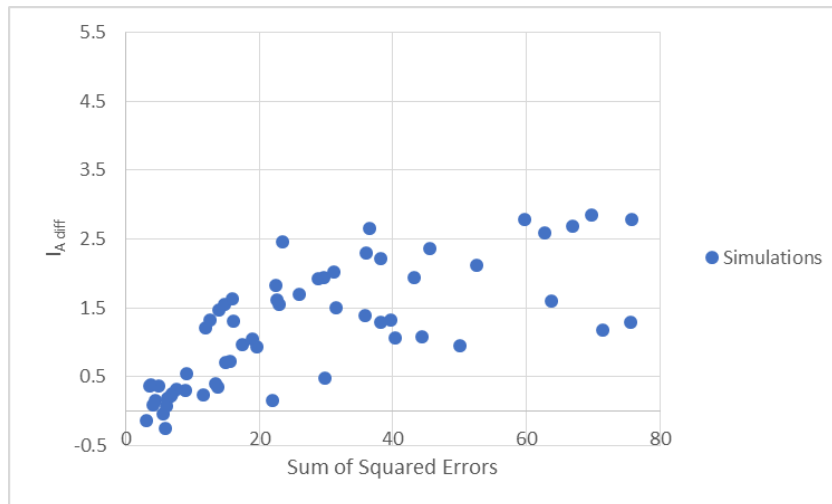


Fig. 6 – Comparison of Simulated Records for 9,950-Year Return Period

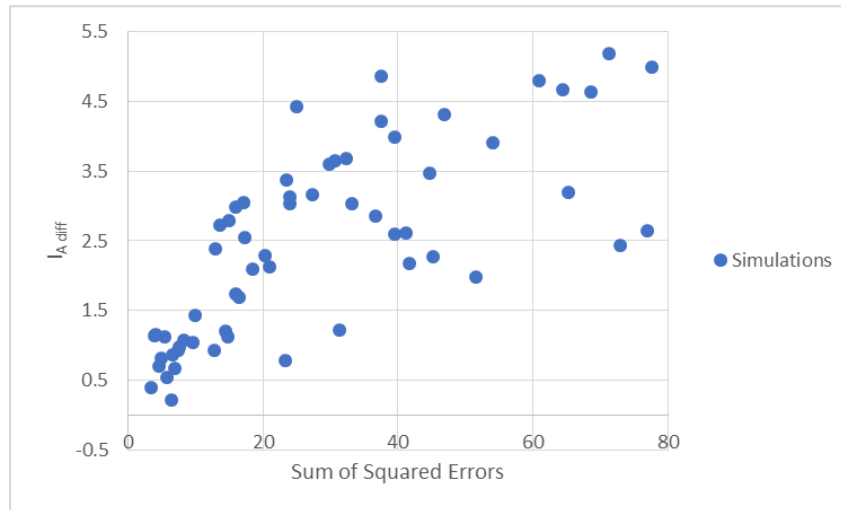


Fig. 7 – Comparison of Simulated Records for 100,000-Year Return Period

The range of the SSE, shown in Table 8, for the simulations is very similar to that for the historical records. The trend of minimal variation in the SSE between return periods is also true for the simulations. It should be noted, however, that the SSE for the simulations is more spread out than the historical records. Therefore, the mean and 90% range are noticeably larger. Recall that the average SSE for the historical records is 14 for all return periods considered. The average SSE for the simulations is between 26 and 28. Also, the 95th percentile SSE extends up to the high 60s to low 70s, compared to the 40s for the historical records.

Table 8 – Comparison of Spectral Acceleration Sum of Squared Errors (SSE)

	Return Periods (years)		
	2,475	9,950	100,000
Range	3 to 73	3 to 76	3 to 78
Mean	26	27	28
90% Range	4 to 67	4 to 70	4 to 71

Table 9 – Comparison of $I_{A \text{ diff}}$ for Simulated Records

	Return Periods (years)		
	2,475	9,950	100,000
Range	-0.43 to 1.74	-0.24 to 2.85	0.22 to 5.20
Mean	0.42	1.03	2.18
90% Range	-0.26 to 1.62	0.07 to 2.68	0.66 to 4.81

Even though the ranges of spectral acceleration SSE for the simulations are higher than those for the historical records, the ranges of the percent difference in Arias intensity are tighter. The upper bound on the percent difference does not exceed 5.20 for any return period. This is significantly less than any upper bound for the historical records. The simulations seem to be more in line from an Arias intensity standpoint with the Maule records than Tohoku. The variation in the mean is a little greater for the simulated records compared to Maule. The ranges, however, are even tighter and the upper bounds are less. This is somewhat unexpected when considering the fact that the scale factors for the simulations are generally greater than the Maule scale factors. The average scale factor for the simulations for the 9,950- and 100,000-year return periods is 4 and 8, respectively. This is in keeping with the Tohoku scale factors, but the range of the Tohoku scale factors is much greater. The 90% range for scale factors for the simulations is 2.6 to 5.4 and 5.2 to 10.7 at the 9,950- and 100,000-year return periods, respectively. For Tohoku, those ranges are 1.2 to 9.5 and 2.5 to 18.8. One



reason the Arias intensity percent difference ranges are lower for the simulations than Maule despite the scale factors may be the unscaled Arias intensities for the simulations compared to Maule. As is shown in Table 3, the geometric mean of the Arias intensity of the unscaled Maule records is much greater than that of the simulated records. Therefore, even though the scale factors for the simulated records are noticeably greater than those for Maule, the fact that the unscaled Arias intensity for the Maule records is, on average, greater than the 9,950-year target likely results in a larger range in the percent difference in the Arias intensity.

The same criteria used for the historical records to determine whether a record is a reasonable match are used here for the simulations. Table 10 details how many simulated records out of 60 met the criterion for spectral acceleration, for Arias intensity, and for both.

Table 10 – Number of Simulated Records Considered Reasonable Matches

Return Period (years)	SA	I _A	Both
2,475	29	45	29
9,950	29	25	22
100,000	27	11	10

Table 10 highlights that less than half of the simulated records are good matches to the spectral acceleration target regardless of the return period. The remainder do not have good spectral shapes compared to the desired target. In comparison, approximately 75% of the historical records are considered reasonable matches to the spectral acceleration targets. At the lower return periods, the Arias intensities of the simulations are a much better match than the spectral accelerations. This changes with increasing return period, with only 11 out of 60 simulated records being a good match at 100,000 years.

7. Comparison of Historical and Simulation Records

Overall, the historical records seem to be a better match to the spectral acceleration targets than the simulations, with approximately 75% of the historical records considered reasonable matches compared to less than 50% of the simulations. This is to be expected because the spectral acceleration targets are largely based on the Tohoku and Maule events. No historical records from the magnitude 9 earthquakes on the CSZ would influence the targets, which is one of the reasons the simulations are beneficial. Comparing the Arias intensities, the percentage of simulated and historical records that are reasonable matches to the target is about the same. For the smaller return periods, more than 50% of the records are reasonable matches, but this decreases to about 20% at the 100,000-year return period. Overall, however, the simulated records seem to be better matches to the Arias intensity targets than the historical records based on the range of the percent difference. The simulations and Maule records seem to be comparable, but the Tohoku records tend to have significantly higher Arias intensities. This could be due to multiple reasons, but one of them is likely the larger scale factors associated with the Tohoku records compared to the Maule and simulated records.

8. Conclusions

Based on how well the records match the spectral acceleration and Arias intensity targets, it seems reasonable to consider some simulated records within a suite used to evaluate the response of a dam, particularly if the evaluation needs to be extended to really long return periods such as 9,950 and 100,000 years. For the site in this study and based on the specific criteria considered in this paper, inclusion of simulated records would increase the number of ground motions from which to choose at the 9,950-year return period from 35 to 57. Consideration of simulated records at 100,000 years would increase the pool of available records from 15 to 26. This represents a 60% increase in the number of records from which to choose at the 9,950 level and a 75% increase at the 100,000 level. If a relatively large number of two-component records are needed, or if closer (more reasonable) matches are desired, these increases could be important.



Another reason to consider inclusion of CSZ simulated records for projects within the Willamette Valley is the fact they were created based on physical characteristics specific to the CSZ, the dominating seismic source for dams in this region. None of the empirical ground motion models used for the targets consider records from magnitude 9 events on the CSZ. The physical differences between Tohoku, Maule, and an event on the CSZ are worth capturing in a structural response analysis, if for no other reason than to better quantify the uncertainty in the structural response. What a magnitude 9 event of the CSZ would look like is uncertain, but the USGS simulations from the University of Washington “M9” project provide quantification of the potential ground motions.

9. Acknowledgements

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