Probabilistic Approach to Design of Seismic Upgrade to Withstand both Crustal and Subduction Earthquake Sources

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ABSTRACT This paper provides an overview on how to make use of the Crustal, In-slab, and Interface hazard values from the GSC 5th generation seismic hazard model. For calculations of seismic slope displacement using the simplified procedure, UHS for the M9 Interface Event and for the M7 non-Interface Event were derived separately at a couple of probability levels, including and beyond the 2475-year level; UHS for 5000-year by extrapolation was verified by results from OpenQuake. Seismic displacements are then calculated separately for the two types of earthquakes for 100 probability points between 1000-year and 10,000-year. The displacement hazard curve for All-Source earthquakes is built by adding the probabilities from each of the two displacement hazard curves at a specific displacement. The paper then presents VERSAT-2D results of probabilistic analyses of the Upper San Fernando dam (with and without ground improvement) subject to ground motions in southwest BC. For the specific structure and site location, it is concluded that displacement hazard contributions for All-Source of earthquakes are dominated by UHS of the M9 Interface Event; and the earthquake magnitude (i.e., duration) has a much greater impact on seismic displacement than UHS. All-Source UHS should not be used, or avoided whenever possible.

Introduction

The 4th generation seismic hazard maps of Canada developed by Geological Survey of Canada (GSC) included hazard values for a probability of 2%/50 years that were adopted in the seismic provisions in the 2005 and 2010 National Building Code of Canada (NBCC). However, these hazard values were derived only from the crustal earthquakes with magnitudes of about 7 (i.e., the M7 Event), while seismic hazards from the Cascadia subduction earthquake with a magnitude of about 9 (i.e., the M9 Event) were evaluated separately using a deterministic approach (Halchuk and Adams 2008). The hybrid method mixing probabilistic and deterministic approaches makes it impossible to design a structure to withstand seismic hazards from all earthquake sources at a specific overall probability level.

The GSC 5th generation seismic hazard model addressed the above issue by using a full Probability Seismic Hazard Analysis (PSHA) to also include seismic hazards from the Cascadia subduction earthquake or the M9 Event. However, the Uniform Hazard Spectra (UHS) from the GSC model creates challenges to civil engineers in how to apply the UHS in engineering design. The two types of earthquake sources represent magnitude difference in two orders (M7 vs. M9); and a M9 earthquake would have 1024 times the energy of a M7 earthquake.

Earthquakes from the two types would result in order of magnitude difference in ground and structural response (such as ground displacements, soil liquefaction potential, and bending moments in bridge piers or in building columns). The large difference in structure response at a specific probability level makes it not appropriate to consolidate such response at the probability level. As such, using the UHS from the GSC model for both the M7 Event and the M9 Event would create dilemma of decision.

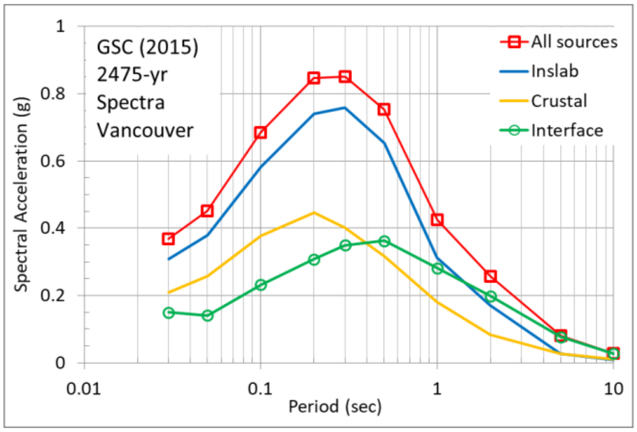
This paper presents detailed procedures of applying the probabilistic approach for engineering performance assessment of structures (buildings, bridges, dams) located in southwest BC where both crustal and subduction earthquakes exist.

Uniform Hazard Spectra for BC

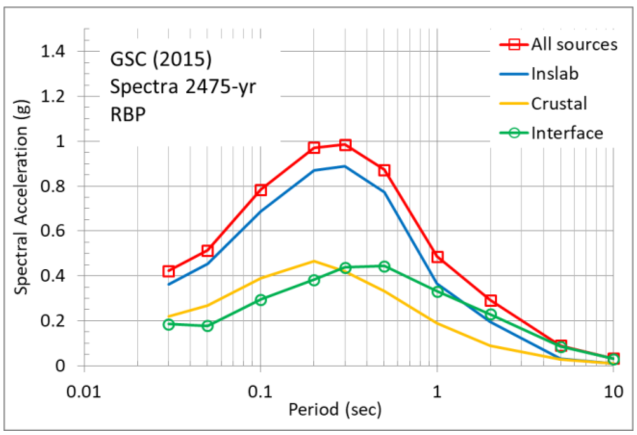
GSC has published results of the 5th generation seismic hazard model in Open File 8090 (Halchuk et al. 2016). For a total of 13148 grid points (10 km by 10 km grid) located in southern BC and western Alberta, the results included seismic peak ground accelerations (PGA) and velocities (PGV), and spectral accelerations at periods of 0.05, 0.1, 0.2, 0.3, 0.5, 1.0, 2.0, 5.0, and 10.0 sec for three types of earthquake sources, namely, the subduction interface (or Interface), the subduction intraslab (or InSlab) and the crustal earthquakes. The All-Source UHS as a part of this report, combining contributions from above three earthquake types, is available from the NRC website “Seismic design tools for engineers” at http://www.earthquakescanada.nrcan.gc.ca/hazard-alea/interpolat/index-en.php.

To illustrate the hazard contribution difference at different locations in BC among the Interface, the InSlab and the Crustal earthquakes, Fig. 1 shows the UHS for a reference ground shear wave velocity of V_{s30} = 450 m/s at the 2475-year earthquake level for grid points at Vancouver (pt. 34044), near Roberts Bank Port (pt. 34101) and in Victoria (pt. 34310).

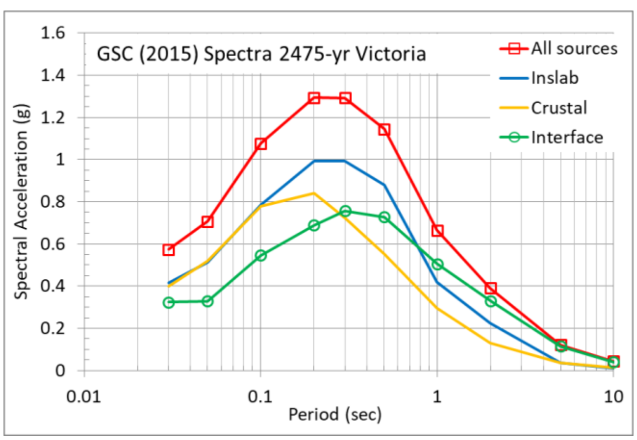
Fig. 1. UHS from GSC 5th Generation Seismic Hazard Model (V_{s30}=450m/s) (a). Vancouver (pt. 34044), i.e., VAN



(b). Roberts Bank Port (pt. 34101), i.e., RBP



(c) Victoria (pt. 34310), i.e., VIC



It appears from Table 1 that the non-Interface[1] or the M7 Event dominates contributions to the UHS in all three site locations. However, we should not be fooled by spectral values when the M7 and the M9 Events are mixed in contribution; in fact, the UHS could be less impacting on ground and structural response than the earthquake magnitude. The duration of a M9 earthquake could be 10 times longer than a M7 earthquake, which is not reflected in the UHS.

Table 1. Spectral Accelerations at 0.3 sec, or S_a(0.3s) in g, from the GSC Model

	All-Source	non-Interface		Interface	
VAN	0.85	0.81	96%	0.35	41%
RBP	0.99	0.94	95%	0.44	44%
VIC	1.29	1.15	89%	0.76	59%

It is proposed to adopt the probabilistic approach for combining the seismic performance (such as displacements) of structures induced from the two distinct types of earthquakes. The probabilistic approach would use the UHS separately for the Interface and for the non-Interface Events; and the method would not require the use of the All-Source spectra. However, for comparing with the non-probability approach, results of non-probability analyses may be discussed, which assumes the All-Source S_a were to be applied for both the Interface and the non-Interface Events.

In order to perform the probabilistic method, UHS at earthquake levels higher than the target level would be required for each of the two earthquake types. For a target earthquake level of 2475-year, UHS at 5000-year and at 10,000-year might be required.

In order to obtain the 5000-year UHS, the GSC hazard values would be extrapolated on the hazard curves at a specific period as spectra published by GSC terminate at 2475-year.

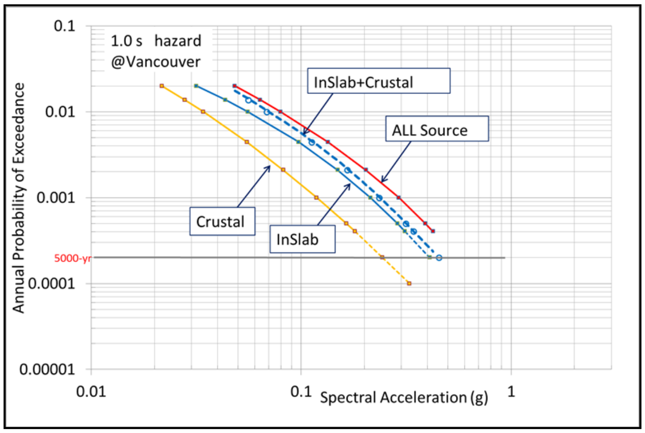
Fig. 2 shows a 2-step procedure for obtaining the type specific UHS at the 5000-year level for the Vancouver site (pt. 34044). It is noted that the non-Interface curve (i.e., combined from Crustal and InSlab curves) is more suitable for extrapolation as its curvature is less; and the extrapolation of the Interface curve would be obtained by subtraction of the All-Source probability value by the non-Interface probability value at a specific S_a. More details of the procedure and images of Excel spreadsheets for performing the extrapolation are shown on the slides presented in a technical lecture for Vancouver Geotechnical Society (VGS) in November 2017 (Wu 2017) and accessible through the VGS website.

GSC Model on OpenQuake Engine

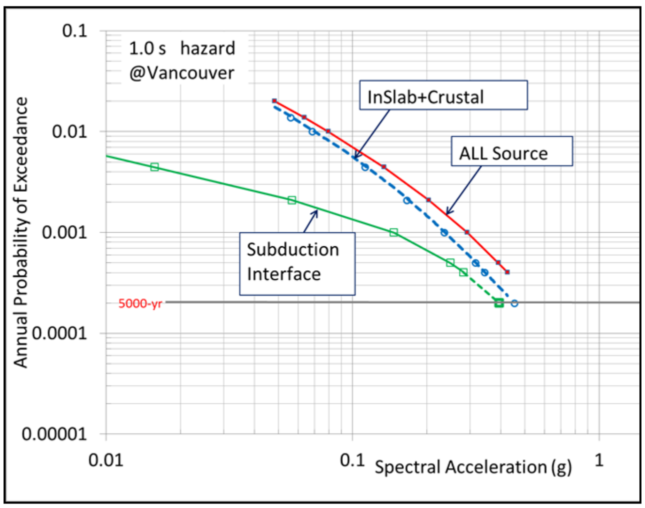
In addition to the extrapolation method described above, a full PSHA has also been conducted for the three locations (VAN, RBP, VIC) using the recently migrated GSC model on the OpenQuake Engine (GEM 2018). OpenQuake is a publically accessible

[1] the Crustal and the InSlab earthquake sources are combined as the non-Interface Event, or the M7 Event.

Fig. 2. Extrapolation of GSC Seismic Hazard Curves beyond 2475-year. (a) Step 1: combining crustal and InSlab



(b) Step 2: extrapolating the curves to 5000-year level



platform for probabilistic seismic hazard and risk analysis. The GSC model on OpenQuake was distributed to the attendees of the 3-day Workshop held in Vancouver on April 11 – 13, 2018. The Workshop was organized by OpenQuake Platform Canada, a collaboration between the Geological Survey of Canada (GSC/NRCan), the Global Earthquake Model (GEM) Foundation and the UBC Earthquake Engineering Research Facility.

Fig. 3 shows the UHS of the two types of earthquakes at the 5000-year earthquake level for the three locations at VAN, RBP, and VIC. The 5000-year UHS by extrapolation (Wu 2017) are compared to the results from OpenQuake. The simple extrapolation method seems to have worked very well, except for the Victoria site where the spectra for the non-Interface event are over-estimated for short periods at and less than 0.2 sec.

Simplified Procedure for Seismic Slope Displacements

Bray and Travasarou (2007) developed simplified procedures for estimating seismic displacement induced by earthquake ground motions from shallow crustal earthquakes along active plate margins (e.g., California earthquakes). Macedo et al. (2017) further extended this framework for estimating displacements induced by ground motions from the Interface Event. Each of the two sets of equations for displacement calculations applies only to the specific type of earthquake sources that were used in developing the procedures.

The probabilistic approach is applied for determining the displacement at a target earthquake level (e.g., 2475-yr) including contributions from both Interface and non-Interface earthquakes. The same example cross section of a dam (Fig. 4) as used by Bray and Travasarou (2007) is used in this study.

According to Bray and Travasarou (2007), the probability of occurrence of zero displacement P(D=0), and the amount of the nonzero displacement (D, in cm) for non-Interface earthquakes can be calculated using the following two equations[2]:

[1] $$P(D=0) = 1 - \Phi(-1.76 - 3.22\ln(k_y) - 0.484T_s\ln(k_y) + 3.52\ln(S_a(1.5T_s)))$$

[2] $$\ln(D) = -1.10 - 2.83\ln(k_y) - 0.333(\ln(k_y))^2 + 0.566\ln(k_y)\ln(S_a(1.5T_s)) + 3.04\ln(S_a(1.5T_s)) - 0.244(\ln(S_a(1.5T_s)))^2 + 1.50T_s + 0.278(M-7)$$

Where,

- yield acceleration coefficient, k_y=0.13 for all
- initial period of the sliding mass, T_s
- earthquake magnitude, M = 7 for the example
- spectral accelerations, $S_a(1.5T_s)$, vary with T_s and earthquake levels (2475-year, 5000-year or other levels).

Similar equations for computing P(D=0) and D for the subduction Interface earthquakes are available from Macedo et al. (2017), with a specific M = 9 being used for the example cross section.

It must be noted that the probability for nonzero displacement calculated from Eq. [2] is conditional probability and should be calculated from P(D=0) and the annual exceedance probability (AEP) related to D, using the following equations:

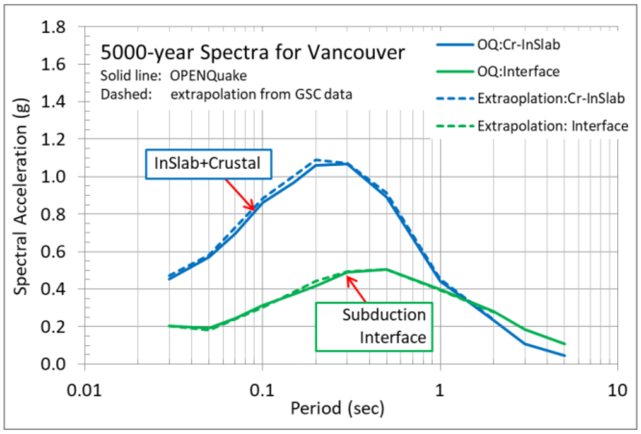
[3] P(D>d) = [1-P(D=0)] • AEP

For example, assuming a nonzero displacement (D) is calculated using S_a from spectra with AEP of 0.001 (or 1000-year earthquake) and the probability

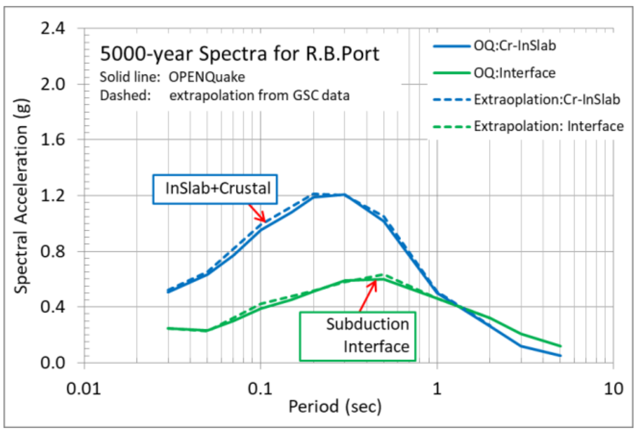
[2] assumed to be also applicable to the InSlab earthquakes.

Fig. 3. 5000-year spectra from the GSC model by extrapolation versus by OpenQuake (OQ)

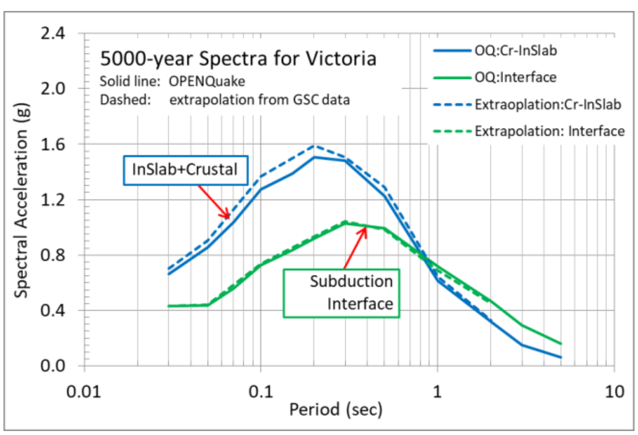
(a). Vancouver (pt. 34044)



(b). Roberts Bank Port (pt. 34101)

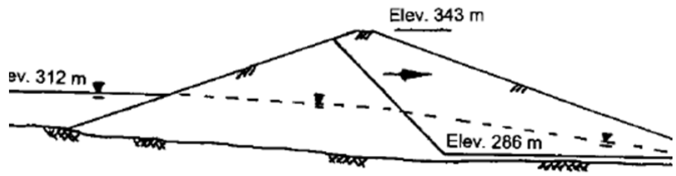


(c) Victoria (pt. 34310)



for zero displacement at this S_a is P(D=0) of 0.184, then the overall probability for the occurrence of D is 0.001 times 0.816 or 0.000816 (i.e., 1225-year). As such, unless the probability for zero displacement is zero, the displacement calculated from spectra of a earthquake level (e.g., 1000-year) would not carry the same probability level as the earthquake event, as illustrated in Wu (2017).

Fig. 4. Example Cross Section for Displacement Calculations, after Bray and Travasarou (2007)



Using the simplified procedures, seismic slope displacements were calculated separately for the two types of earthquake, the Interface Event (Macedo et al. 2017) and the non-Interface Event (Bray and Travasarou 2007). A total of 100 probability points were used between 0.001 (1000-year) and 0.0001 (10,000-year) for computing the displacement hazard curves for the two types of earthquakes, as shown in Fig. 5. The $S_a(1.5T_s)$ values corresponding to each of the 100 probability values were used in the calculations, with interpolation between the 1000-year and the 2475-year and so forth for each earthquake type. The All-Source displacement hazard curve was then built by adding the probability values of the two earthquake types at a specific displacement.

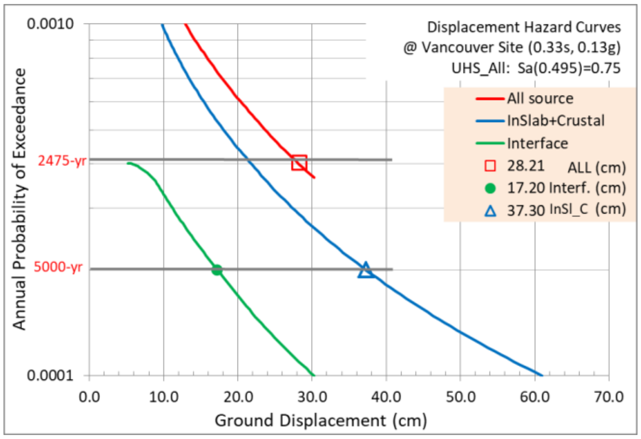
The 2475-year seismic slope displacements of the sliding mass for All-Source are shown in Table 2; they are also compared with the displacements from each of the two earthquake types at the 5000-year probability level. The observations made in the study are summarized below:

- Half Probability Rule: D_2475-year_All-Source (2%/50-years) must exist between D_5000-year_M7 and D_5000-year_M9, i.e., at half of the All-Source probability or at 1%/50 years.
- Largest at the Same Probability Rule: D_2475-year_All-Source must be greater than D_2475-year_M7 and D_2475-year_M9. At the same probability level, D for All-Source is always the largest.
- D_10,000-year for the earthquake type with smaller D_5000-year, but D_2475-year for the other type, would be required in order to bracket the D for All-Source at the 2475-year probability level.

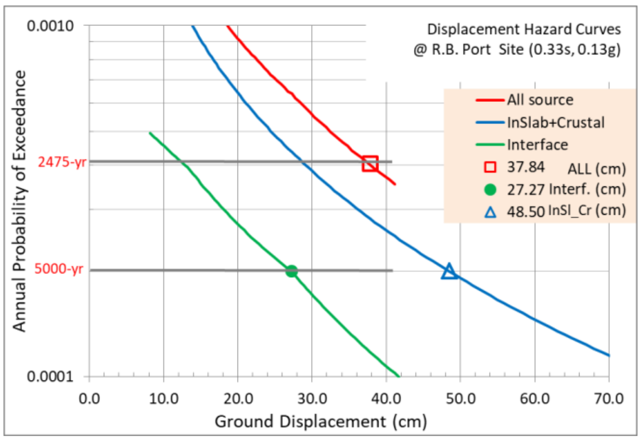
The above observations are useful tips that could be used in planning to minimize the number of required dynamic analyses, especially when Method A "use Mean" (Wu 2017) is used to process results of numerical analyses that is time consuming to complete an analysis.

In the conventional non-probability approach, one might use the $S_a(1.5T_s)$ values from the All-source UHS in the calculation of seismic displacements from the M9 Interface Event. The displacements calculated as such are shown in the last column of Table 2. It is seen that the displacements are over

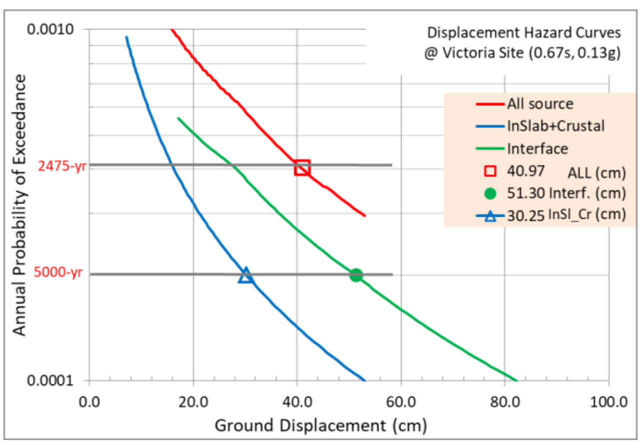
Fig. 5. Seismic slope displacement hazard curves from simplified procedures (a). A stiff site (T_s=0.33s, k_y=0.13) in Vancouver (pt. 34044)



(b). A stiff site near Roberts Bank Port (pt. 34101)



(c) A soft site (T_s=0.67s) in Victoria (pt. 34310)



estimated by 34% for a VAN stiff site (T_s = 0.33s, S_a (0.5s) = 0.754 g), and by 31% for a VAN soft site (T_s = 0.67s, S_a (1.0s) = 0.425 g). The simplified procedure assumes that the site does not involve soil liquefaction and the equations by Macedo et al. (2017) are indeed applicable to Vancouver and other sites in BC. Further analyses with site involving soil liquefaction, later in the study, demonstrate that the use of All-Source UHS for the M9 Interface Event is not adequate; and the probabilistic method must be used for adequate determination of displacements from All-Source earthquakes.

Table 2. Seismic Slope Displacements, D (cm)

Site	T_s (s)	Disp. (cm) by Probability			S_a ($1.5T_s$) by UHS	Disp. (cm) by 2475-yr *UHS*
		5000-yr M7	2475-yr ALL	5000-yr M9		
VAN	0.33	37.3	28.2	17.2	0.754	37.8
	0.67	14.0	15.2	16.4	0.425	19.9
RBP	0.33	48.5	37.8	27.3	0.873	49.1
	0.67	18.2	20.4	23.8	0.486	26.2
VIC	0.33	70.2	65.0	60.8	1.144	77.6
	0.67	30.2	41.0	51.3	0.665	48.3

The Upper San Fernando Dam Subject to the 1971 Ground Motion

The Upper San Fernando Dam (USF Dam) under the 1971 San Fernando earthquake was analysed using the effective stress finite element dynamic analysis using the ground motion at the dam site as was used by Seed et al. (1973); the results of that analysis were reported in Wu (2001). Release 98 of the computer program VERSAT-2D (Wu 1998) was used in the 2001 analyses of the dam using a relatively coarse finite element mesh with 678 nodes and 625 elements. In the current 2018 study, the 2001 USF dam model has been re-analysed with two additions of (1) using version 2018 of VERSAT-2D (WGI, 2018) and (2) using a finer mesh with 2835 nodes and 2704 elements (see Fig. 6). More model details of VERSAT-2D dynamic analyses are provided in Wu (2001) for the USF dam; and subsequently for many other structures in Wu and Chan (2002), Wu et al. (2006), Finn and Wu (2013), Sweeney and Yan (2014), and Wu (2015), BC Hydro (2016).

The soil parameters used in the 2018 study are the same as in the 2001 study, as shown in Table 4. The computed displacements from the 2001 and the 2018 studies are compared on Table 3 with the actual displacements measured after the 1971 San Fernando earthquake. The results indicate robustness and consistence between the 2001 and the 2018 VERSAT-2D modelling.

Table 3. Displacements (m) by VERSAT-2D

Locations (X-hori.; Y-vert.)		Measured in 1971	Wu (2001)	This Study
U/S crest Node 1150	X	1.50	1.50	0.60
	Y	-0.76	-0.73	-0.48
D/S crest Node 1962	X	2.20	2.26	2.63
	Y	-0.43	-0.40	-0.45

Fig. 6 The Upper San Fernando Dam Model with a Finer Finite Element Mesh, modified from Wu (2001)

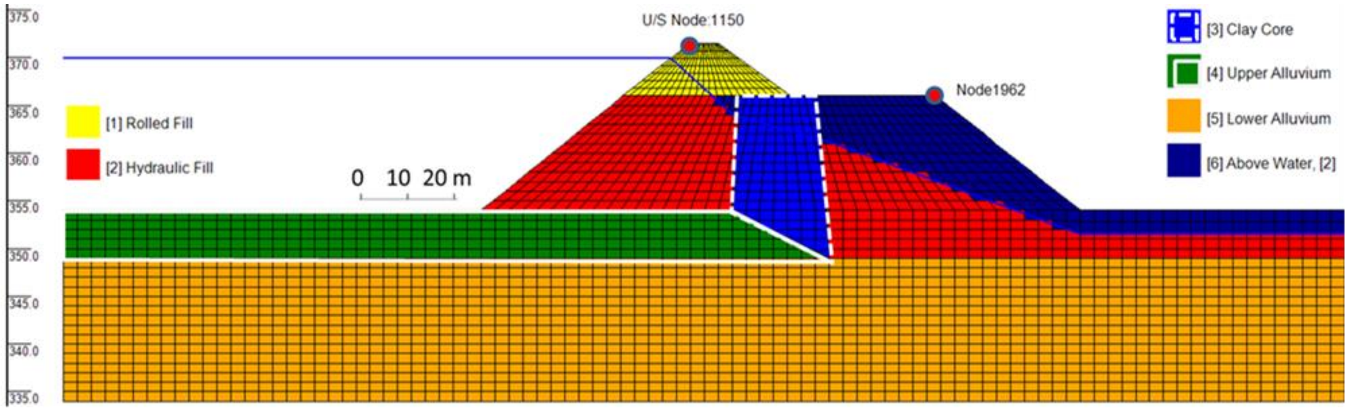


Table 4. Soil Parameters Used in VERSAT-2D Dynamic Analyses, after Wu (2001)

Soil unit	Soil material	Unit weight (kN/m^3)	Strength parameters		Stiffness parameters*		
			c' (kPa)	ϕ' (°)	K_{2max}	K_g	K_b
1	Rolled fill	22.0	124.5	25	52	1128	2821
2	Hydraulic fill	19.2	0	37	30	651	1630
3	Clay core	19.2	0	37	—†	651	1630
4	Upper alluvium	20.3	0	37	40	868	2170
5	Lower alluvium	20.3	0	37	110	2387	6000

*Modulus exponents ($m = n = 0.5$) were used for all soil units.
†For the clay core, the low-strain shear modulus was suggested by Seed et al. (1973) as $G_{max} = 2300S_u$, with $S_u = 57.45$ kPa (1200 psf).

The USF Dam Subject to Ground Motions in BC

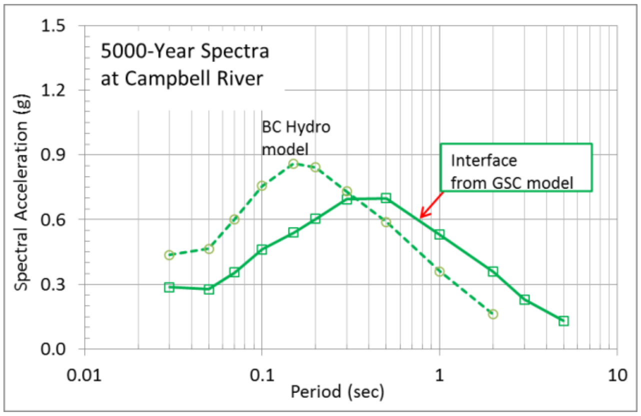
In order to demonstrate the methodology of the probabilistic approach in seismic design of structures in southwest BC, dynamic analyses of the USF dam are continued, however, assuming the dam is located on firm ground in Vancouver Island, near Campbell River at N50.0600, W125.3080.

Fig. 7 shows a comparison of UHS, at the Campbell River location, from the GSC Model and from the BC Hydro Model (BC Hydro 2012). Despite the difference in V_{s30} between the two models (450 m/s for GSC model and 760 m/s for BC Hydro model), it is noted that the difference in the two spectra (shape and magnitude) between the two models is not caused by the V_{s30}; it has more to do with the ground motion prediction equations (GMPEs) and the characteristic of seismic source zones used in each model. Noticeably, the GSC model placed a significant weight (50%) on a simulation-based GMPE for the Interface Event (Atkinson and Adams 2013). It is known that Cyber Shake or simulation-based ground motions are more applicable for long period motions; and they have been included or considered in developing design spectra in US, such as for the City of Los Angles. Atkinson and Adams (2013) acknowledged that Cyber Shake GMPE has over predicted the ground motions of the 2011 Japan M9 Tohoku earthquake.

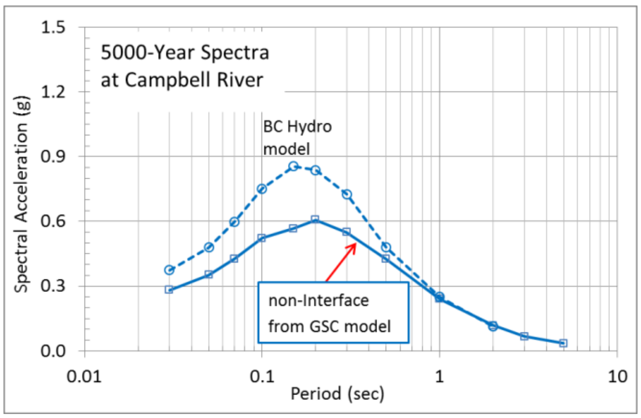
For this study, the UHS from the BC Hydro model and the GSC model has been averaged (i.e., with equal weight of 0.5 and 0.5 for each) for a specific earthquake level. Fig. 8 shows the UHS used in this study for the two types of earthquakes at 1000-year, 2475-year, 5000-year and 10,000-year. As seen in Fig. 8, the spectra at other levels are scalable from the 5000-year level (the base level) for the entire range of periods (0.03 – 2.0 sec). This makes it possible to automate the dynamic analyses at various probability levels.

A total of 11 Interface earthquake records (5 from 2011 Tohoku M9 Earthquake and 6 from Chile Maule M8.8 Earthquake), were selected, rotated (for a better fit) and then linearly scaled to fit the target Interface spectra in Fig. 8(a). Another set of 11 non-Interface records (6 from crustal earthquakes and 5 from InSlab earthquakes) were developed to fit the target non-Interface spectra shown in Fig. 8(b). It is noted that except these in the NGA West2 database many of the records are raw and not processed; thus they are processed ahead of being used for rotating

Fig. 7. Comparison of response spectra at Campbell River site from GSC Model and BC Hydro Model for the Interface and non-Interface Events (a). Subduction Interface Event



(b). non-Interface (Crustal and InSlab combined)



and linear scaling. A name list of the earthquake records used in the dynamic analyses is provided in Table 5. Vertical ground motions were not applied in this study.

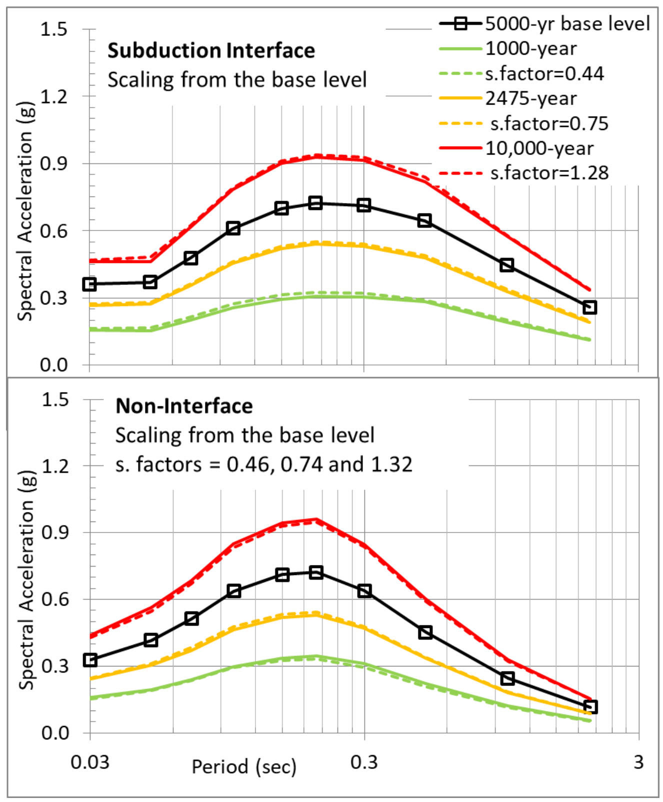
Displacement hazard curves from the probabilistic analyses of the as-is condition of the USF dam are shown in Fig. 9. Based on the results, it is predicted that the dam would have 3.3 m, 5.0 m and 6.0 m of mean horizontal X-displacement at the downstream crest (Node 1962); and 0.95 m, 1.22 m and 1.50 m of mean settlements at the dam crest (Node 1150), at the 2475-year, 5000-year and 10,000-year earthquake levels, respectively.

More importantly to mention, at the 2475-year level, the mean X-displacement at Node 1962 is 0.40 m for the non-Interface M7 Event but it is as high as 3.0 m for the Interface M9 Event. Without using the probabilistic method, it would be a great dilemma to arrive at a displacement from the M7 and the M9. Note that on the spectra plot in Fig. 8 the $S_a(0.3s)$ for the M9 Interface is only slightly higher than the $S_a(0.3s)$ for the non-Interface M7 Event.

Table 5. List of Earthquake Records Used in the Probabilistic Analysis of Seismic Displacements

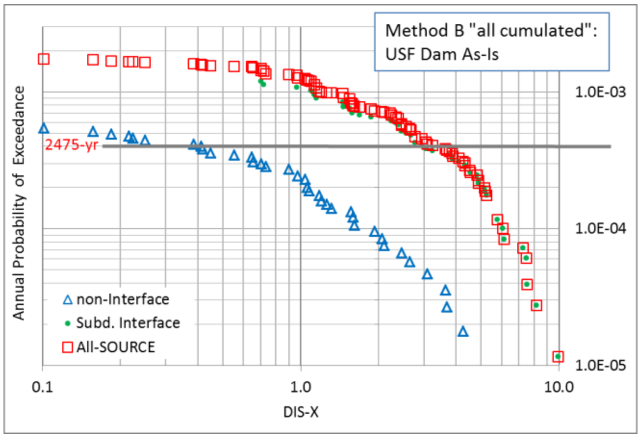
Interface Earthquakes	Non-Interface Earthquakes
2011 Japan Tohoku	**InSlab**
FKSH16	2001 Nisqually Gig Harbour
IWTH24	2001 Nisqually at Olympia
MYG016	2005 Japan Miyagi Oki MYG013
MYGH06	1965 Puget Sound at Olympia
MYGH09	1949 Washington at Olympia
2010 Chile Maule	**Crustal**
ANTU	1994 Northridge, at Chalon Rd.
ME at La Florida	1979 Imperial Valley, at CPE
MAT at Matanzas	1999 Kocaeli, at Izmit
HSOR at Penalolen	1989 Loma Prieta, at SJTE
GSIT at Puente Alto	1978 Iran Tabas, at Tabas
SJCH	1999 Taiwan Chi Chi, at TCU071

Fig. 8. Spectra for Campbell River, consolidated from GSC and BC Hydro models, and its scalable nature



Estimated deformation of the as-is USF dam after an approximately 25,000-year earthquake is shown in Fig. 10 which shows a large horizontal displacement of 9.95 m and a settlement of 2.26 m at the dam crest. With the limited amount (~ 1.5 m) of freeboard, the dam could have been overtopped should such a big earthquake hit the dam. Note that the probability at such a low level is approximately as more analyses at lower probabilities would be required to determine it accurately.

Fig. 9. Displacement hazard curve from probabilistic analyses of USF dam: As-is. (a). Horizontal at the D/S Crest (Node 1962), Disp-X



(b). Settlement at Dam Crest (Node 1150), Disp-Y

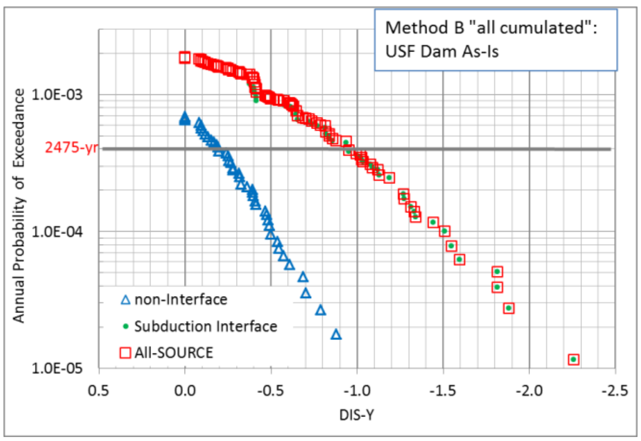
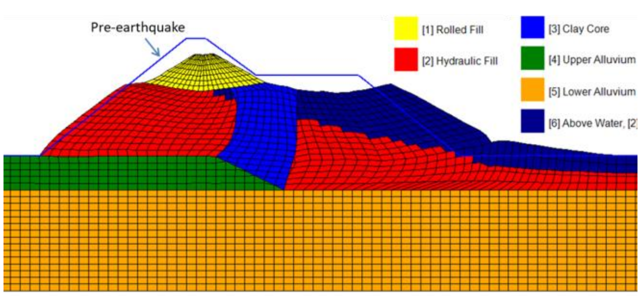


Fig. 10 Estimated Deformation of the As-is USF Dam after an approximately 25,000-year Earthquake



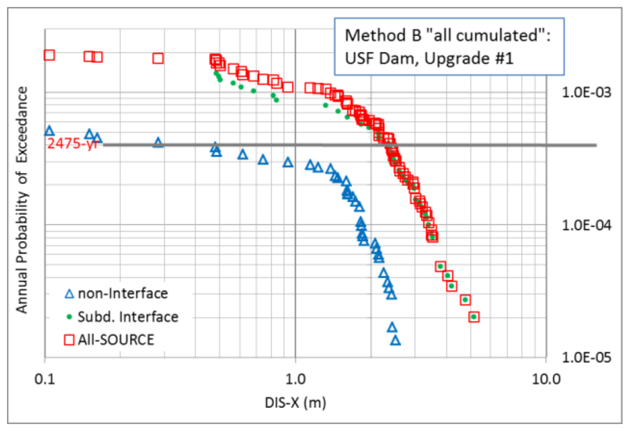
Seismic Upgrade Option #1

The USF Dam has been taken out of service after the 1971 San Fernando Earthquake. Thus, it is used herein as a case-history dam for the study of possible upgrade options using the probabilistic method for design. In current study, two upgrade options have been considered: 1). improvement of the liquefiable hydraulic fill under the downstream shoulder for a limited width of 50 m; and 2). improvement for a larger zone extending to the toe of the downstream slope. Also, it has been assumed that the hydraulic fill (Material #2 in VERSAT-2D model) after ground improvement would not liquefy subject to all levels of earthquakes, i.e., the treated zone in Fig. 12 has been assumed to have the same properties as the hydraulic fill above water (Material #6 in the model).

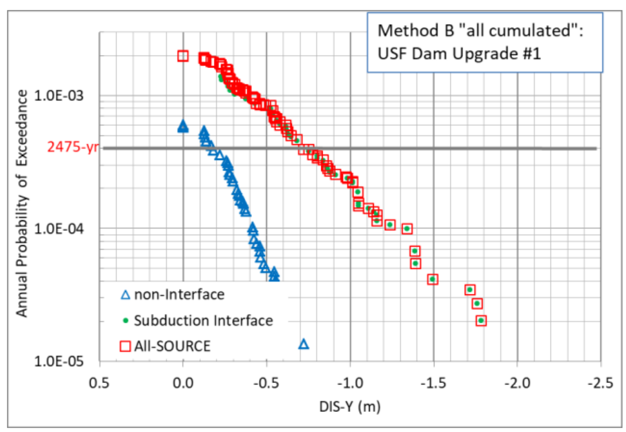
Displacement hazard curves from the probabilistic analyses of the dam with Upgrade #1 are shown in Fig. 11. The analysis results show that the dam would have 2.4 m, 3.0 m and 3.4 m of mean horizontal displacements at the downstream crest (Node 1962); and 0.72 m, 1.0 m and 1.25 m of mean settlements at the dam crest (Node 1150), at the 2475-year, 5000-year and 10,000-year, respectively.

Fig. 11 Displacement hazard curve from probabilistic analyses of USF dam: Upgrade #1.

(a). Disp-X at Node 1962 (D/S crest)

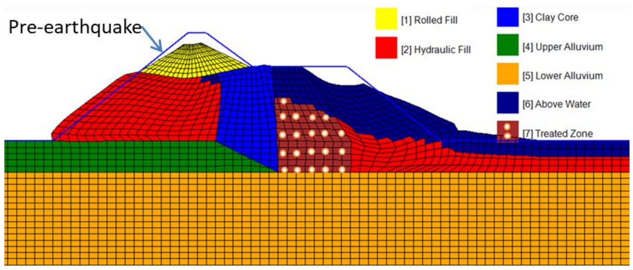


(b). Disp-Y at Node 1150 (Dam Crest)

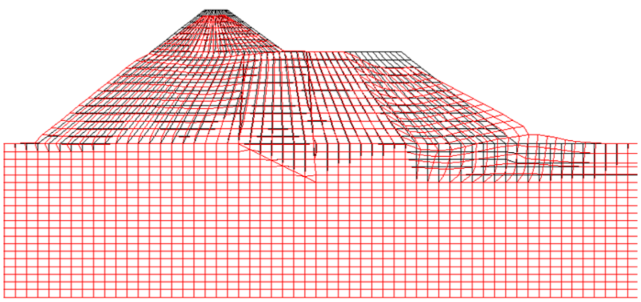


With implementation of Upgrade #1, as shown in Fig. 12(a), the dam would still suffer large ground deformation in areas upstream and downstream of the treated zone under an extremely high ground motion (approximately 25,000-year level). The settlement at the dam crest would be about 0.72 m should the design earthquake level be set at 2475-year. However, the deformation of the dam at the

Fig. 12. Estimated Deformation of USF Dam with Upgrade #1 (a). after an approximately 25,000-year Earthquake



(b). Deformation after a 2475-year Earthquake



2475-year earthquake level, as shown in Fig. 12(b), may be acceptable depending on the upgrade requirements or design criteria.

Effect of Upgrade Option #2

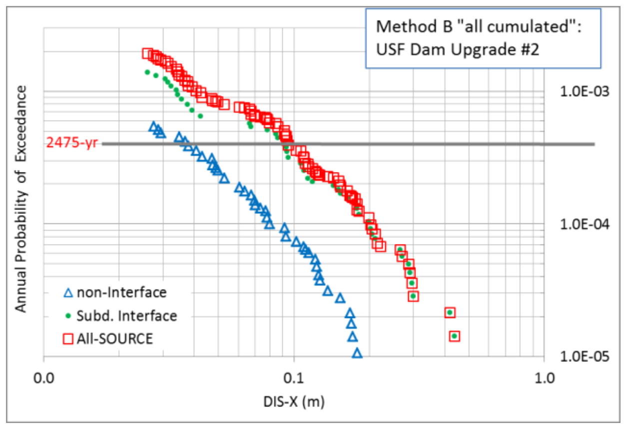
Displacement hazard curves from the probabilistic analyses of the dam with Upgrade #2 are shown in Fig. 13. Based on the results, it is predicted that the dam would have 0.1 m, 0.15 m and 0.2 m of mean horizontal displacements at the downstream crest (Node 1962); and 0.86 m, 1.15 m and 1.4 m of mean settlements at the dam crest (Node 1150), at the 2475-year, 5000-year and 10,000-year earthquake levels, respectively.

Although Upgrade #2 would reduce the downstream displacements significantly from Upgrade #1, the amount of crest settlement was not reduced; in fact it has caused more crest settlements (see Fig. 14). This is largely expected as the dam tends to move upstream more when the downstream becomes less deformable.

Automation of 264 Dynamic Runs by VERSAT-2D (version 2018)

All dynamic time-history analyses were performed using VERSAT-2D version 2018 (WGI, 2018) with the capability of auto-running multiple analyses in one input file. As a minimum, two input files would be required to accomplish a complete probabilistic analysis involving two types of earthquakes, one input file for the M7 non-Interface Event and the other one for the M9 Interface Event. The total number of runs managed in one input file is equal to the number of earthquake levels times the number of earthquake records.

Fig. 13 Displacement hazard curve from probabilistic analyses of USF dam: Upgrade #2 (a). Disp-X at Node 1962 (D/S crest)



(b). Disp-Y at Node 1150 (Dam Crest)

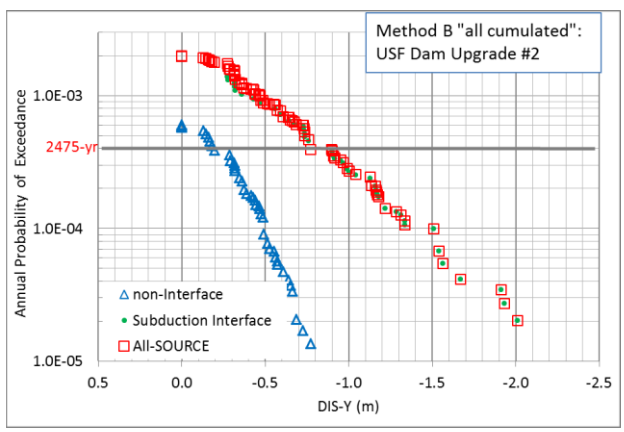
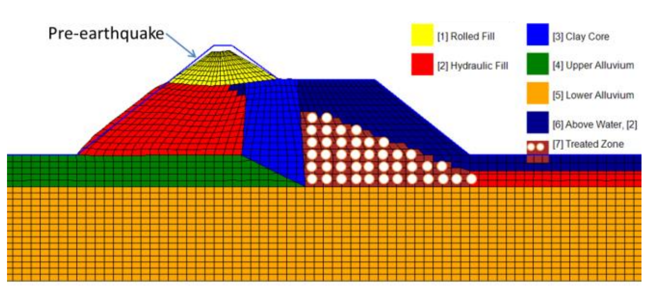


Fig. 14 Estimated Deformation of USF Dam with Upgrade #2 after a 2475-Year Earthquake



For probabilistic analysis of the as-is USF dam, a total of 88 dynamic runs were completed in two input files, which include 44 runs (11 records at 4 probability levels) for the M9 Interface Event and another 44 runs for the M7 non-Interface Event. After completion of the 88 runs, the program will auto-generate the displacement (or other response items such as factor of safety against liquefaction) hazard curves at any pre-selected points of interest, similar to Fig. 9 for Node 1150 (Dis-Y) and 1962 (Dis-X). Similarly, a total of 88 runs were completed for USF Dam Upgrade # 1 and Upgrade #2. Therefore, for this study, a total of 264 dynamic runs (3 x 88 each) were completed in about 3 days (24 hours a day) of computer time on a PC.

Final Remarks on Probabilistic Approach to Seismic Response

Results of probabilistic analyses by VERSAT-2D, targeting at the 2475-year displacements from all earthquake sources for the USF dam subject to ground motions of Campbell River in BC, indicate:

- Displacement hazard contributions for All-Source are dominated by UHS of the M9 Interface Event; the contribution from UHS of the M7 non-Interface Event is small and potentially negligible;
- The earthquake magnitude (i.e., duration) has a much greater impact on seismic displacements than the UHS;
- All-Source UHS should not be used, or avoided whenever possible, for assessing structure response in southwest BC.

However, it must be reminded that the relative contributions to displacements from the M7 and the M9 Events, as stated above, are for the specific structure and site location used in this study.

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