October 6, 2014

A Probability Approach to Structural Response for Uniform Seismic Hazard Including Both Crustal and Subduction Earthquakes

Guoxi Wu, Ph.D., P.Eng.

ABSTRACT

A probabilistic seismic hazard analysis is usually conducted to determine uniform hazard response spectra at a site and deaggregation of earthquake magnitudes and site-source distances, at various Annual Exceedance Probability (AEP) levels,. Once a seismic hazard level (AEP) is selected for a design evaluation, conventional analyses such as limit equilibrium stability analysis or finite element deformation analysis are conducted using seismic loads corresponding to the selected AEP. The structural response (such as stresses, ground displacements, or stability factor of safety) is evaluated deterministically for the AEP using standards, specifications and design codes by comparing them with established failure criteria or ultimate stability requirements.

For structures in a seismic zone containing both crustal and subduction earthquakes, the above standards-based approach faces difficulties to reconcile structural response, resulting from crustal earthquakes (M=7 for example) as well as from subduction earthquakes (M=9 or larger). The response values from the two earthquake sources are often not in the same order of magnitude.

A probability approach to structural response would conduct two separate analyses to compute the probability distribution of any required structural response, one for crustal and another one for subduction earthquake source. This approach would involve response analyses at multiple earthquake probability levels in order to calculate the probability distribution for response. The total probability of exceedance for any structural response is the summation of the probability of exceedance from crustal earthquakes and the probability of exceedance from subduction earthquakes. This probability approach would not consider uncertainties in structure properties such as soil shear strength or liquefaction resistance; but it separates probability contributions resulting from two distinctly different earthquake sources. Therefore, this is not a risk analysis; but it can be expanded to become a risk analysis.

Seismic Hazard for Subduction Interface Event

Based on results of BC Hydro seismic hazard model, the seismic hazard curves for subduction interface events for a Lower Mainland dam site are constructed using results of deaggregation. The seismic hazard curves at selected period of T=0.01s, 0.15s, and 0.5s are shown in Figure 1, for both the subduction interface earthquake and combined all earthquake sources. The later includes crustal earthquakes, subduction intraslab and interface earthquakes.

From the hazard curves, seismic hazard spectra for the subduction interface earthquake at a given annual exceedance probability (AEP) can be obtained. The seismic hazard spectra at AEP of 1/10,000 for subduction interface earthquakes are shown in Figure 2, together with the uniform hazard response spectra (UHRS) for all earthquake sources.

The spectral accelerations (Sa) at T=0.01 sec (the PGA level) and at T=0.5 sec for the subduction interface earthquakes are about 63% of the Sa values for the UHRS at these periods. In addition, subject to strong ground motions at a high return period (such as 1000-year or higher depending on structure characteristics), structure response can become nonlinear. Nonlinear response under a subduction interface earthquake could become more or larger than that under a crustal earthquake because the interface earthquake has a much longer duration than a crustal earthquake.

The result of nonlinear structure response depends on both magnitude and duration of an input ground motion. Thus, structural response from subduction interface earthquake may require separate determinations.

Input Ground Motions and Linear Scaling

A total of five acceleration or velocity time histories, recorded from past earthquakes, were selected as input ground motions for nonlinear dynamic analysis. These earthquake ground motions consist of three records from crustal earthquakes and two records from subduction earthquakes as follows:

- 1999 Taiwan Chi-Chi M7.6 earthquake, record at TCU071, W component
- 1994 US Northridge M6.7 earthquake, record at Chalon Rd, 070 component
- 1978 Iran Tabas M7.4 earthquake, record at Tabas, LN component
- 2011 Japan Tohoku M9.0 earthquake, record at MYG009 (Taiwa), EW component. This record (MYG) was baseline corrected by BC Hydro after it was downloaded from the NIED K-Net database of Japan.
- 2010 Chile Maule M8.8 earthquake, record at Hualane, L component. This record (HUAL) was downloaded from a database provided by the Center for Engineering Strong Motion Data (CESMD).

The two subduction records (MYG and HUAL) are linearly scaled to fit hazard spectra for subduction interface earthquakes. The scaling is targeted at an assumed period range of interest from 0.3 to 1.0 sec, which may not be appropriate for some more rigid or stiff structures. The scaling factors for AEPs from 1/100 to 1/50,000 are given in Table 1. The scaled response spectra for AEP of 1/10,000 are shown in Figure 3, which indicates scale factors of SF=0.49 and 0.534 for MYG and HUAL records, respectively. It is noted that after scaling factors for 1/10,000 are obtained using a weighting method over the period range of interest, the scaling factors for all other AEPs are then taken to be linearly proportional to the spectral acceleration at T=0.5 s, i.e., scaled by Sa(0. s).

The three crustal records are not linearly scaled to fit the target hazard spectra for crustal plus intra-slab earthquakes as it should be; instead the UHRS are used as the target spectra for this scaling. This choice in scaling would result in about 10% over-shooting on target spectra for the crustal plus intra-slab earthquakes; but it would be a “common practice” approach that people adopt for such seismicity conditions at the site. However, it is kept in mind that the “common practice” solution would result in slightly over-estimation on structure response for crustal plus intra-slab earthquakes.

The scaling factors for the three crustal records for AEPs from 1/100 to 1/50,000 are given in Table 2. The scaled response spectra for AEP of 1/10,000 are shown in Figure 4, which indicates scale factors of SF=0.615, 1.597 and 0.439 for TCU, CHL and TAB records, respectively.

Table 1 Scaling Factors for the Two Subduction Records

AEPs	Interface Sa(0.5s)	Scaling Factors (SF)	
		Hualane (HUAL)	Myg009 (MYG)
1/100	0	Not applicable	
1/475	0.07	0.082	0.089
1/1000	0.13	0.152	0.165
1/2475	0.24	0.280	0.305
1/5000	0.33	0.385	0.420
1/10,000	0.42	0.490	0.534
1/50,000	0.71	0.828	0.903

Table 2 Scaling Factors for the Three Crustal Records

AEPs	UHRS Sa (0.5s)	Scaling Factors (SF)		
		Chi Chi (TCU)	Chalon (CHL)	Tabas (TAB)
1/100	0.096	0.088	0.229	0.063
1/475	0.208	0.192	0.497	0.137
1/1000	0.286	0.263	0.684	0.188
1/2475	0.407	0.375	0.973	0.268
1/5000	0.520	0.479	1.243	0.342
1/10,000	0.668	0.615	1.597	0.439
1/50,000	1.120	1.032	2.677	0.737

Deterministic Approach Results

Dynamic time-history analyses are carried out to compute the factors of safety (FS) against soil liquefaction for a 1D soil column, using the two subduction and the three crustal records and the scale factors shown in Table 1 and 2. The analysis model is shown in Figure 5, which contains a 6 m thick medium dense sand layer with SPT $(N_1)_{60}$ =22 at a depth of 10 to 16 m. A total of 33 analyses are complete, including 12 runs for subduction records (2 records and 6 runs each), and 21 runs for crustal records (3 records and 7 runs each).

The results of FS at soil element No. 7 (in the middle of the medium dense sand zone) for the 33 runs are shown in Figure 6(a), which indicate discrete FS values at a given AEP (i.e., deterministic probability) for the five input earthquake records.

The results indicate that, at low level of shaking with a return period less than 1000-year, crustal ground motions result in lower FS than subduction ground motions. However, this trend reverses as the return period becomes larger than approximately 1000-year. At the 10,000-year level, subduction ground motions result in much lower FS (more liquefaction) than crustal ground motions.

It is difficult to determine a seismic liquefaction withstand AEP with FS=1 from results of deterministic or discrete analyses due to large scatter of FS values. AEP of 1/1000 level is probably the closest as four of the five records result in FS between 1.03 and 1.12.

Probability Approach Results

Each AEP on a hazard curve that uses probability of exceedance can be discretized to represent a range of probability as shown in Table 3 and 4. With a weight factor of 1/3 (for three records) or 0.5 (for two records), the probability of occurrence for each of the three crustal records and two subduction records can be calculated and are shown in Tables 3 and 4. The accuracy of analysis and calculation will increase as more AEPS and more number of ground motion records are adopted in the process; that can result in much more efforts of analysis.

The probability of exceedance at a given FS is calculated to be the summation of probabilities of occurrence for all ground motions that result in FS equal to or less than the given FS. This process is carried out separately for the subduction earthquake source zone and for the crustal earthquake source zone. The total probability of exceedance with FS is obtained by adding up probability results for all earthquake source zones. Results of this probability analysis of liquefaction (FS) data are presented in Figure 6(b).

Based on results using the crustal earthquake records, the seismic liquefaction withstand (FS=1) is a seismic event with AEP of 1/2,000. However, the seismic liquefaction withstand drops to a 1/800-year event using the total combined curve, i.e., when the subduction interface is also included.

Table 3 Probability of Occurrence for Each of the Three Crustal Records

Individual Probability (AEPs)	Probability Range (x 10^{-3})	Incremental Probability	Weight factors	Probability of occurrence for each record
1/100	15 - 5	0.01	0.33	0.003300
1/500	5 - 1.4	0.0036	0.33	0.001188
1/1000	1.4 - 0.7	0.0007	0.33	0.000231
1/2500	0.7 - 0.3	0.0004	0.33	0.000132
1/5000	0.3 - 0.15	0.00015	0.33	0.000050
1/10000	0.15 - 0.05	0.0001	0.33	0.000033
1/50000	0.01 - 0.05	0.00004	0.33	0.000013

Table 4 Probability of Occurrence for Each of the Two Subduction Records

Individual Probability (AEPs)	Probability Range (x 10^{-3})	Incremental Probability	Weight factors	Probability of occurrence for each record
1/100	15 - 5	0.01	Not applicable	
1/500	5 - 1.4	0.0036	0.5	0.001800
1/1000	1.4 - 0.7	0.0007	0.5	0.000350
1/2500	0.7 - 0.3	0.0004	0.5	0.000200
1/5000	0.3 - 0.15	0.00015	0.5	0.000075
1/10000	0.15 - 0.05	0.0001	0.5	0.000050
1/50000	0.01 - 0.05	0.00004	0.5	0.000020

Figure 1 Seismic hazard curves including subduction interface at periods of 0.01 sec (PGA level), 0.15 sec and 0.5 sec from the BC Hydro Seismic Model

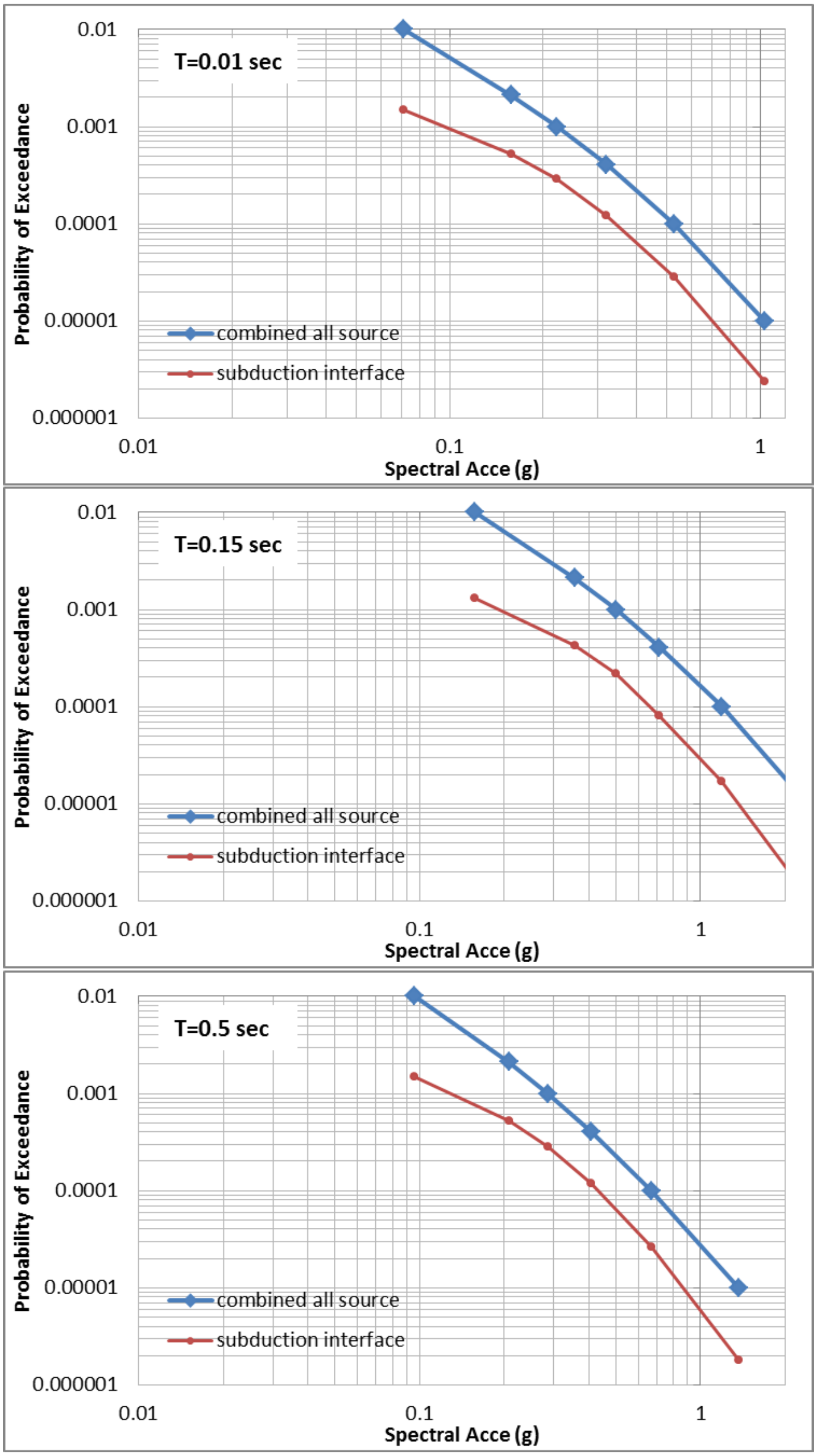


Figure 2 Seismic hazard spectra at AEP of 1/10,000 for subduction interface, crustal plus intra-slab earthquake sources, and all combined sources (UHRS)

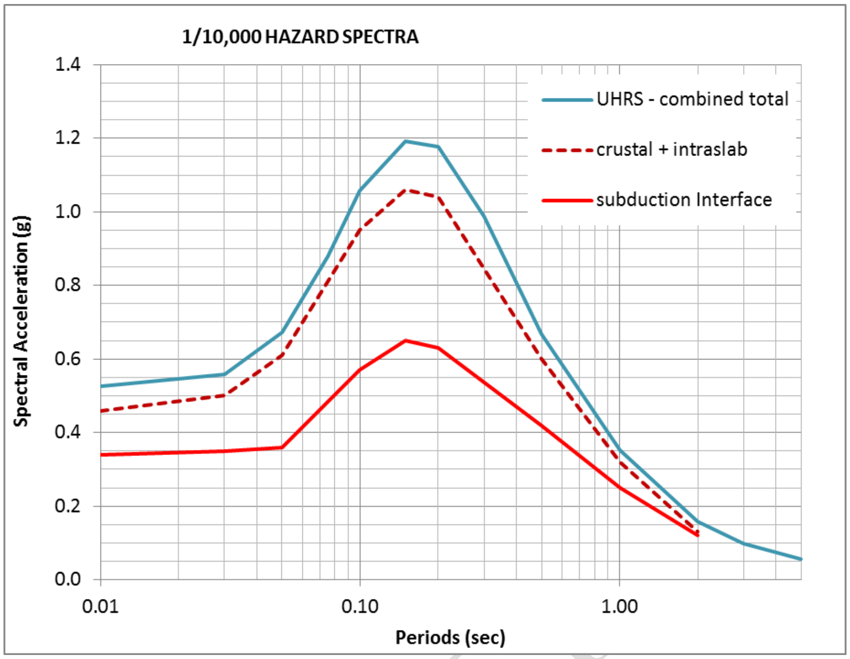


Figure 3 Response spectra for two subduction earthquake records scaled to fit 1/10,000 seismic hazard spectra for subduction interface events

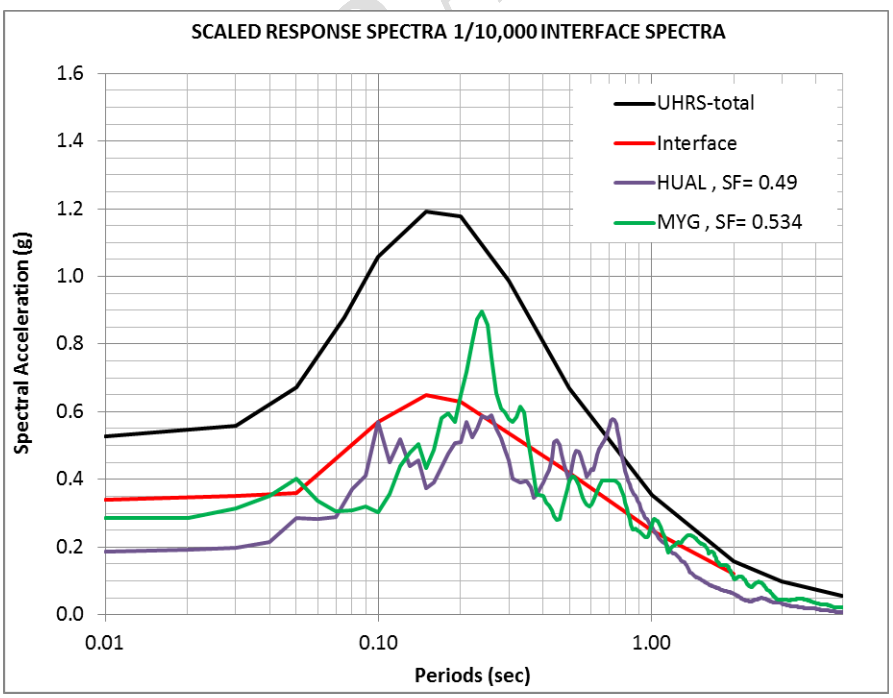


Figure 4 Response spectra for three crustal earthquake records scaled to fit 1/10,000 seismic hazard spectra for crustal plus intra-slab events

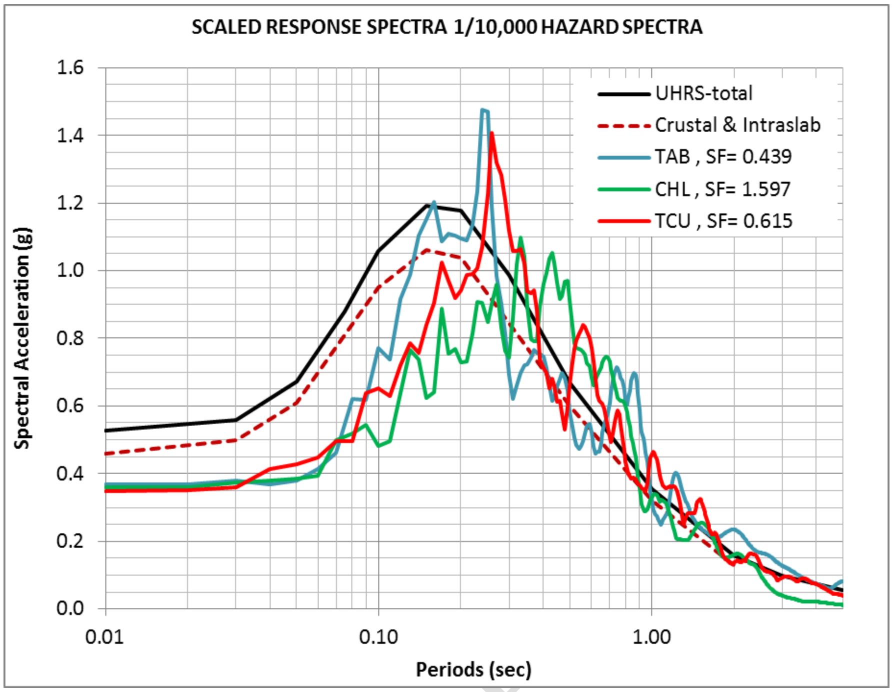


Figure 5 Finite Element Model for Liquefaction Analysis of a 1D Soil Column

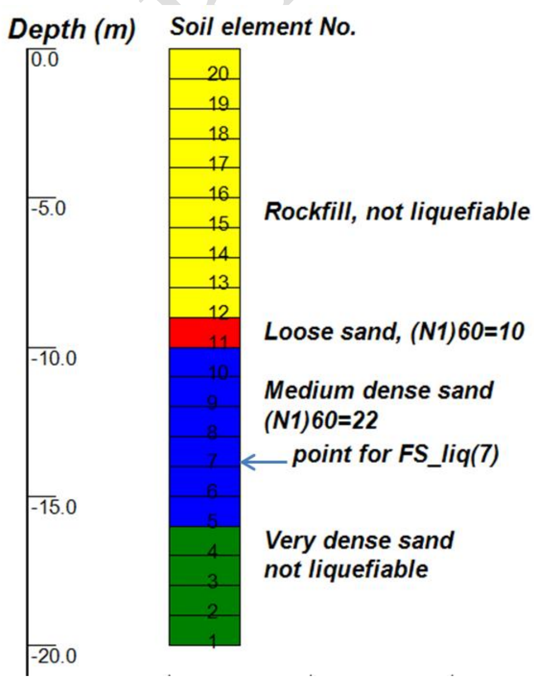
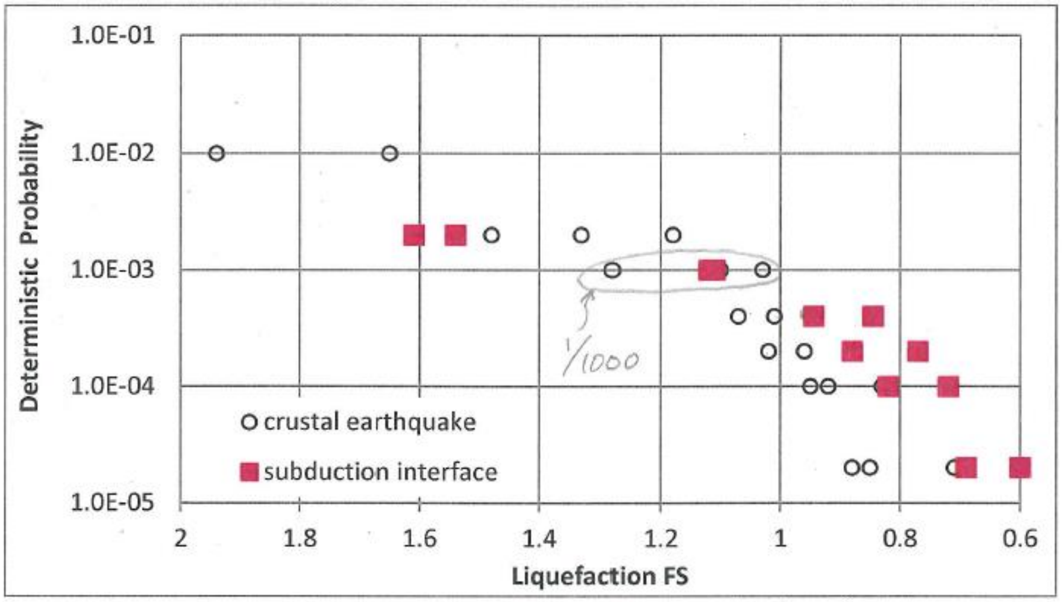


Figure 6 Results of liquefaction analysis FS with (a) deterministic analysis; (b) probability analysis

(a) Deterministic analysis



(b). Probability analysis