Probability Approach for Ground and Structure Response to GSC 2015 Seismic Hazard including Crustal and Subduction Earthquake Sources

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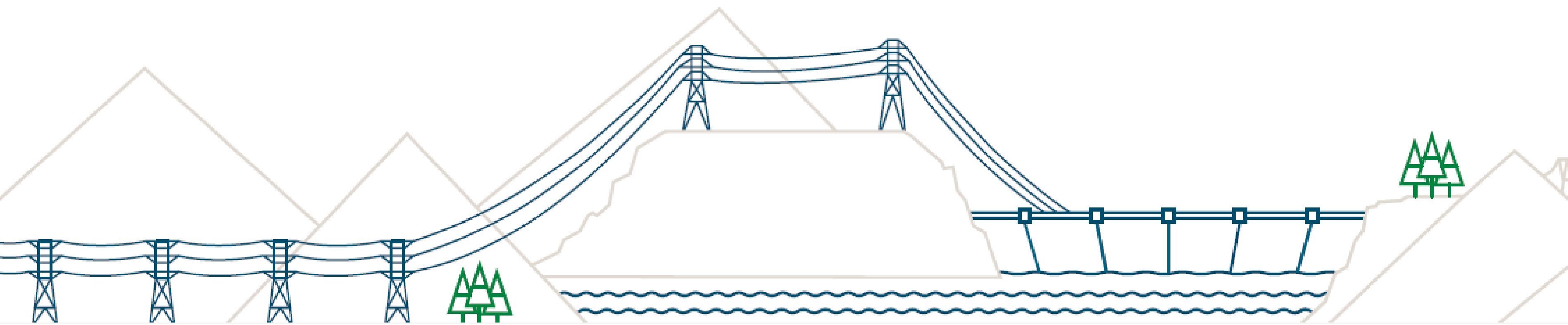
on November 14, 2017



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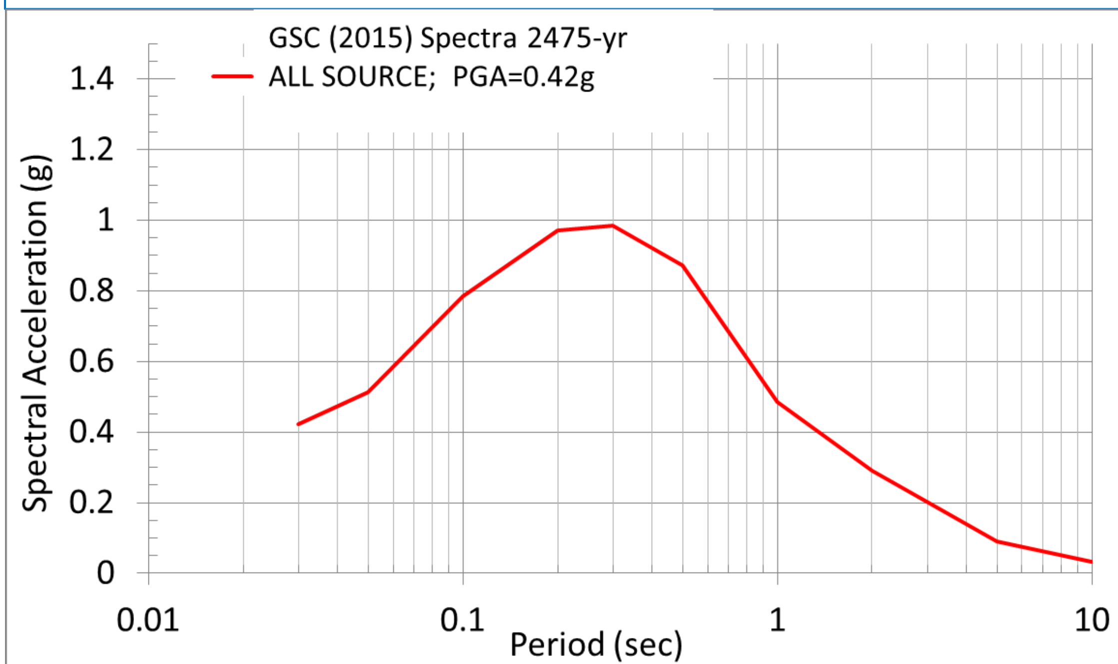
Problem of Interest:

For a site in the Greater Vancouver Area, under a seismic event with a 2% probability of exceedance in 50 years (2475-yr level) with the uniform hazard spectra (UHS) below as defined by GSC (2015) 5th generation seismic hazard model, to determine:

1. **Seismic slope sliding displacement for a yield acceleration a_y of 0.13g (Bray and Travasarou, 2007)**
2. **Liquefaction potential of sands at a site with measured shear wave velocities with depths and Vs = 450 m/s for depths from 114 – 146 m, assuming (N1)60 = 24 for the sands.**



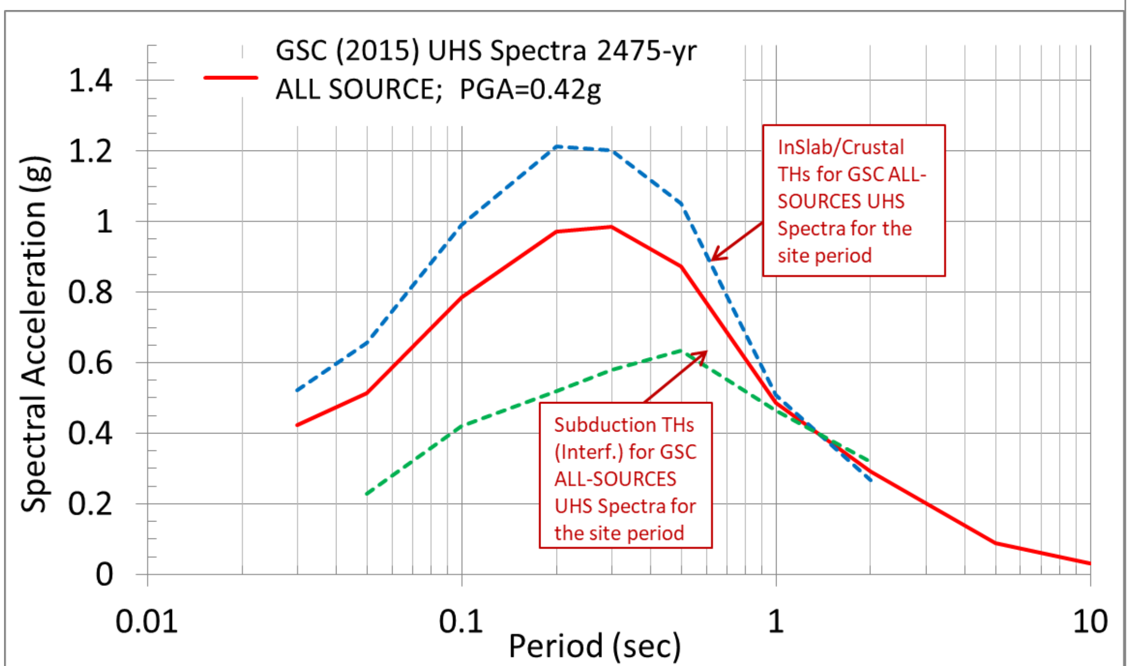
Characteristics of Earthquakes in BC:

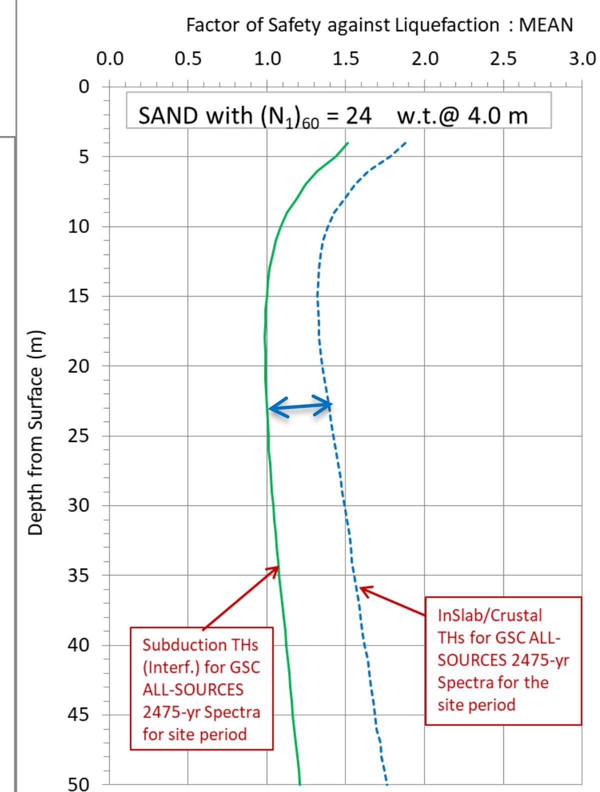
- Two earthquake sources with dramatically different magnitudes (M~7 for InSlab/Crustal and M~9 for Subduction Interface)

Possible Answers to Q2:

1. **Select InSlab/Crustal time histories for GSC ALL-SOURCES Spectra for the site period, e.g., 1.0 to 2.0 sec**
2. **Select subduction interface time histories for GSC ALL-SOURCES Spectra for the site period**

How to close the gap between the two sets of result?





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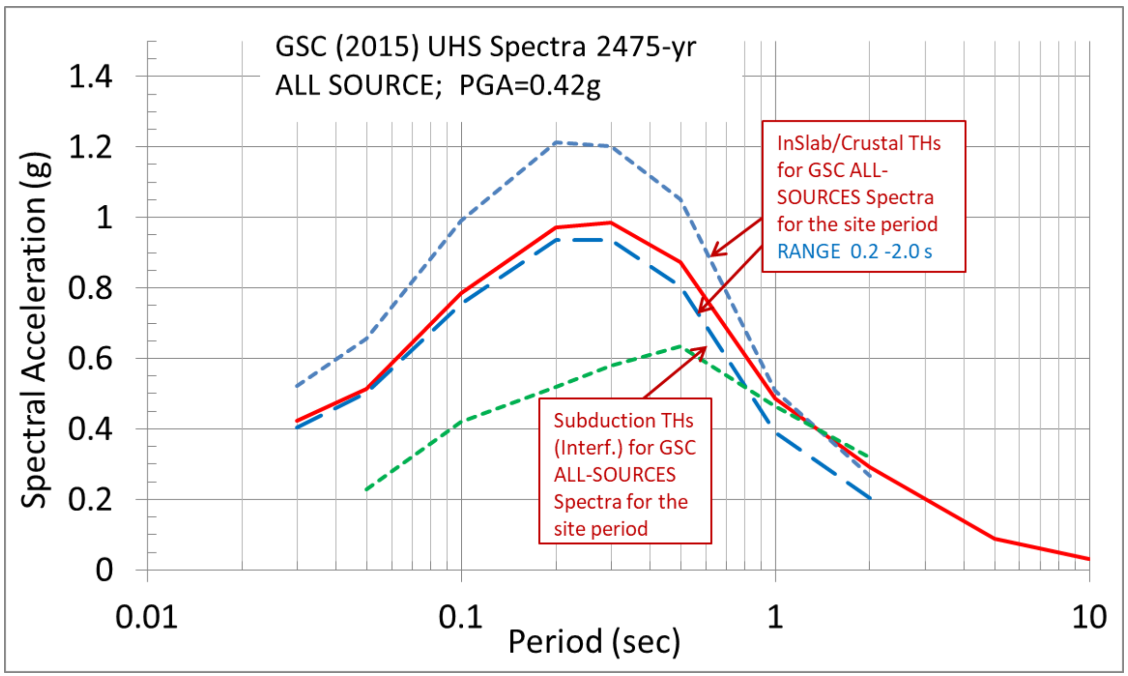
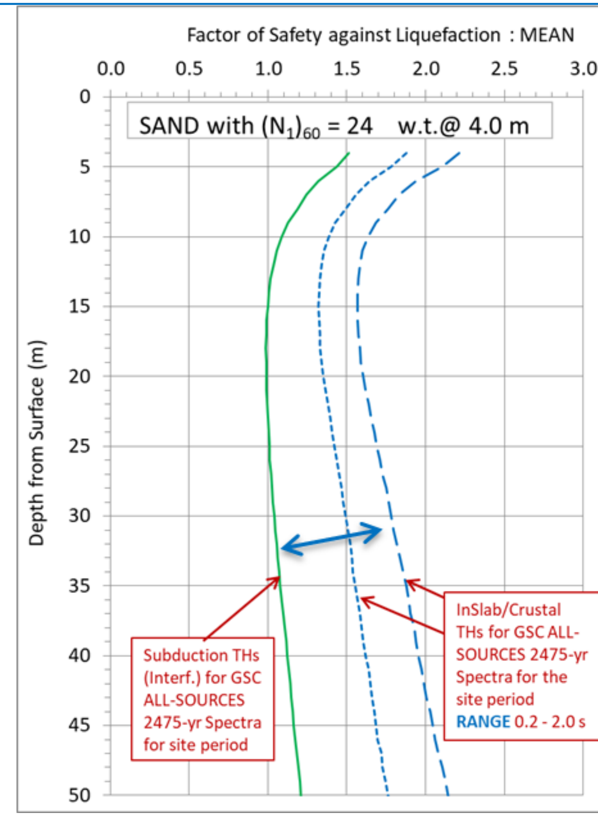
How about adjusting InSlab/Crustal source target spectra to:

Somewhere between the two blue dash lines

The gap getting larger
Subduction Interf.: Yes, will liquefy.
Inslab/Crustal: No, will not liquefy.
Seismic engineer's answer=?





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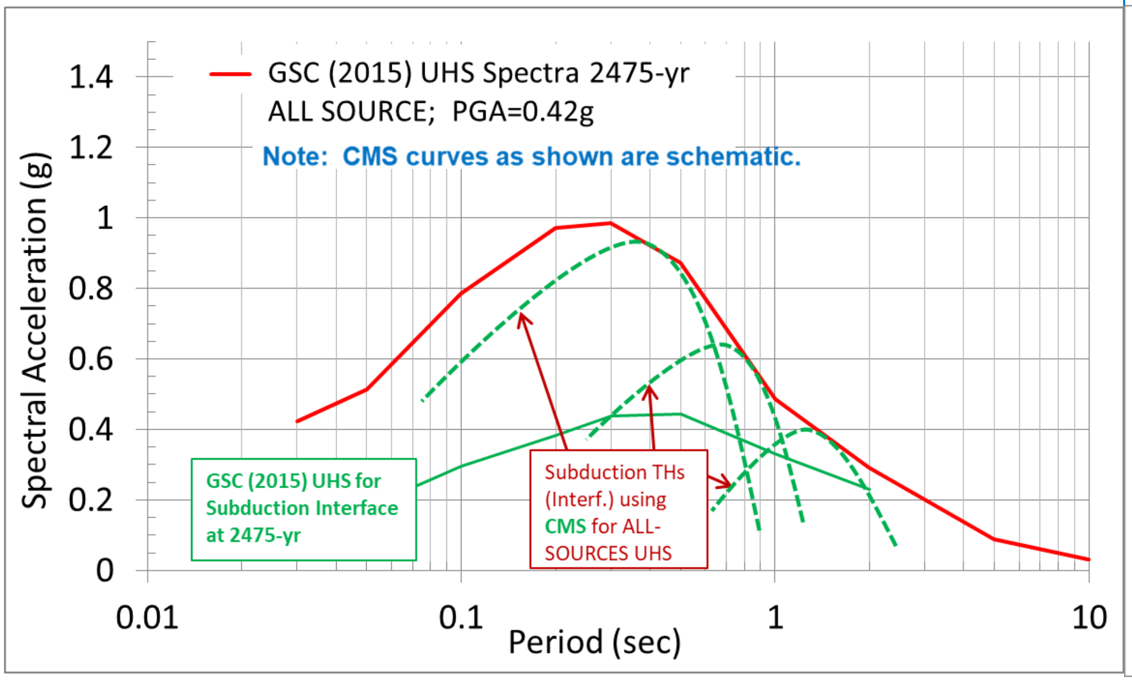
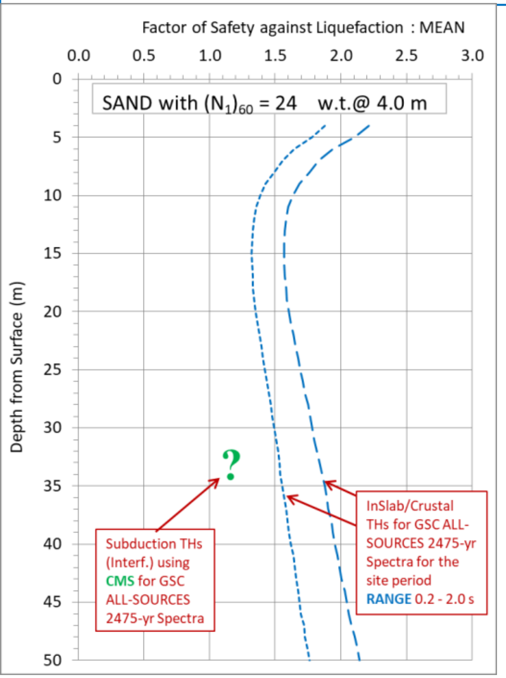
How about using conditional mean spectra (CMS) for subduction interface events?

1. Can the CMS represent the scenario spectra for subduction EQs when they are anchored to the ALL-SOURCE UHS (including both M~7 and M~9 earthquake sources)? Has CMS method been developed from data of single source (M~7) or from multiple sources (M~7 and M~9)?
2. Are any natural and recorded THs available for CMS of M~9 ?

Not sure where the results from CMS will plot





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Outline

Probability Approach for Ground and Structure Response to
GSC 2015 Seismic Hazard including
Crustal and Subduction Earthquake Sources

1. Seismicity in southwestern Canada (120 min, skipped)
2. GSC (2015) Fifth Generation Seismic Hazard Model and Probability Seismic Hazard Analysis (PSHA) results up to 2%/50 years (i.e., 2475-yr) for crustal, in-slab, interface subduction, and all source combined (i.e., ALL-SOURCE).
3. Developing UHS for 5000-yr Level (1%/50 years) for two seismic sources: Cascadia subduction interface (Interf.) and Inslab/Crustal from GSC (2015) PSHA results
4. Seismic slope displacements from empirical equations (Bray and Travasarou 2007, Macedo et al. 2017) for a probability of 2%/50 years
5. Factors of Safety (FoS) against liquefaction of a soil column using nonlinear finite element time history analyses (VERSAT, Wutec 2016) for a probability of 2%/50 years
6. Conclusion Remarks

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GSC (2005) fourth generation seismic hazard model

- PSHA does not include hazard from Cascadia subduction earthquake

The fourth 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 from only the crustal earthquake sources (magnitude in the order of 7), while seismic hazards from the Cascadia subduction earthquake source (magnitude in the order of 9) were evaluated separately using a deterministic approach for hazard assessment based on the distances to the site. The hybrid method mixing probabilistic and deterministic approaches makes it impossible to design a certain structure to withstand seismic risk at a given overall probability level including all earthquake sources.

GSC (2015) fifth generation seismic hazard model

- PSHA includes hazard from Cascadia subduction earthquake

- The 2015 GSC fifth generation seismic hazard model addressed the above issue by providing seismic hazard maps (e.g., 2%/50 years) with seismic hazards from all earthquake sources including the contribution from the Cascadia subduction earthquake. However, the total Uniform Hazard Spectra (UHS) possesses challenges to civil engineers in how to apply the UHS in engineering design as the two earthquake sources have dramatically different magnitudes (M7 for crustal and M9 for subduction interface) and thus they would result in ground and structural response (such as ground displacement, soil liquefaction potential, or bending moment in building columns) in an order of magnitude difference. Using the UHS_ALL-Source for crustal and subduction earthquake sources would be inadequate for engineering performance assessment or in design of new buildings.
- crustal, in-slab, and interface subduction hazard values are provided in the 2015 GSC Model for the 13148 grid points (10 km by 10 km)

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GSC (2015) fifth generation seismic hazard model

Ground motion parameters for use with the National Building Code of Canada

2015 edition

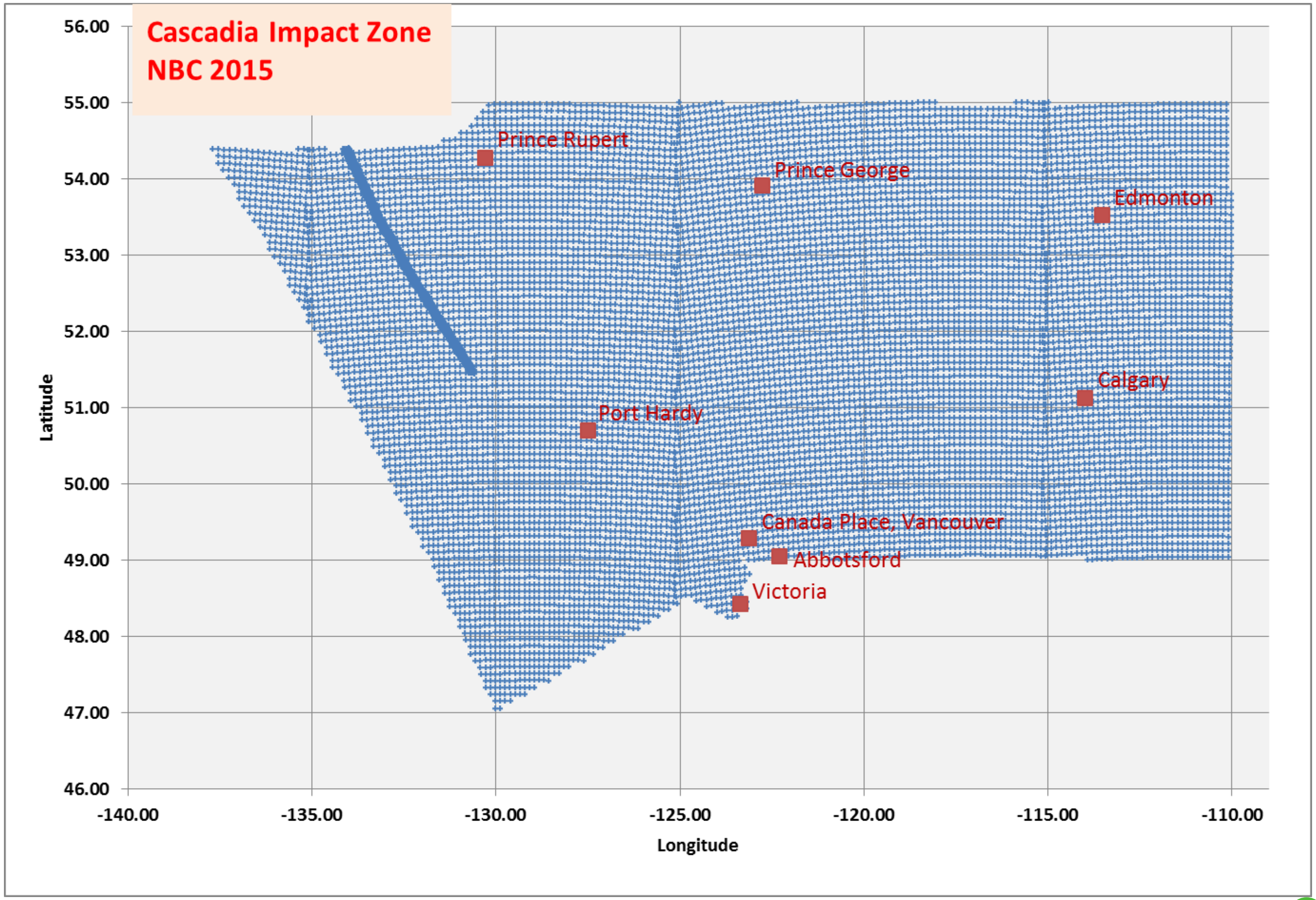
- **Get 2015 hazard values**
- 2015 National hazard maps
- Hazard values for very low probabilities (1 in 5000, 1 in 10,000 years)

Open Files

- Open File 7576: Fifth Generation Seismic Hazard Model Input Files as Proposed to Produce Values for the 2015 National Building Code of Canada
- Open File 7724: Seismic Hazard Earthquake Epicentre File (SHEEF2010) used in the Fifth Generation Seismic Hazard Maps of Canada
- Open File 7893: Fifth Generation Seismic Hazard Model for Canada: Grid values of mean hazard to be used with the 2015 National Building Code of Canada
- Open File 8090: Fifth generation seismic hazard model for Canada: crustal, in-slab, and interface hazard values for southwestern Canada ← GSC Open File 8090

GSC (2015) fifth generation seismic hazard model

2015 GSC Model 13148 grid points (10 km by 10 km) impacted by Subduction



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GSC (2015) fifth generation seismic hazard model

Open File 8090: Contains 13148-point data for crustal, in-slab, and interface hazard values for southwestern Canada (PGA, PGV, Sa at 0.05, 0.1, 0.2, 0.3, 0.5, 1.0, 2.0, 5.0, 10.0 s)

44 grid files below

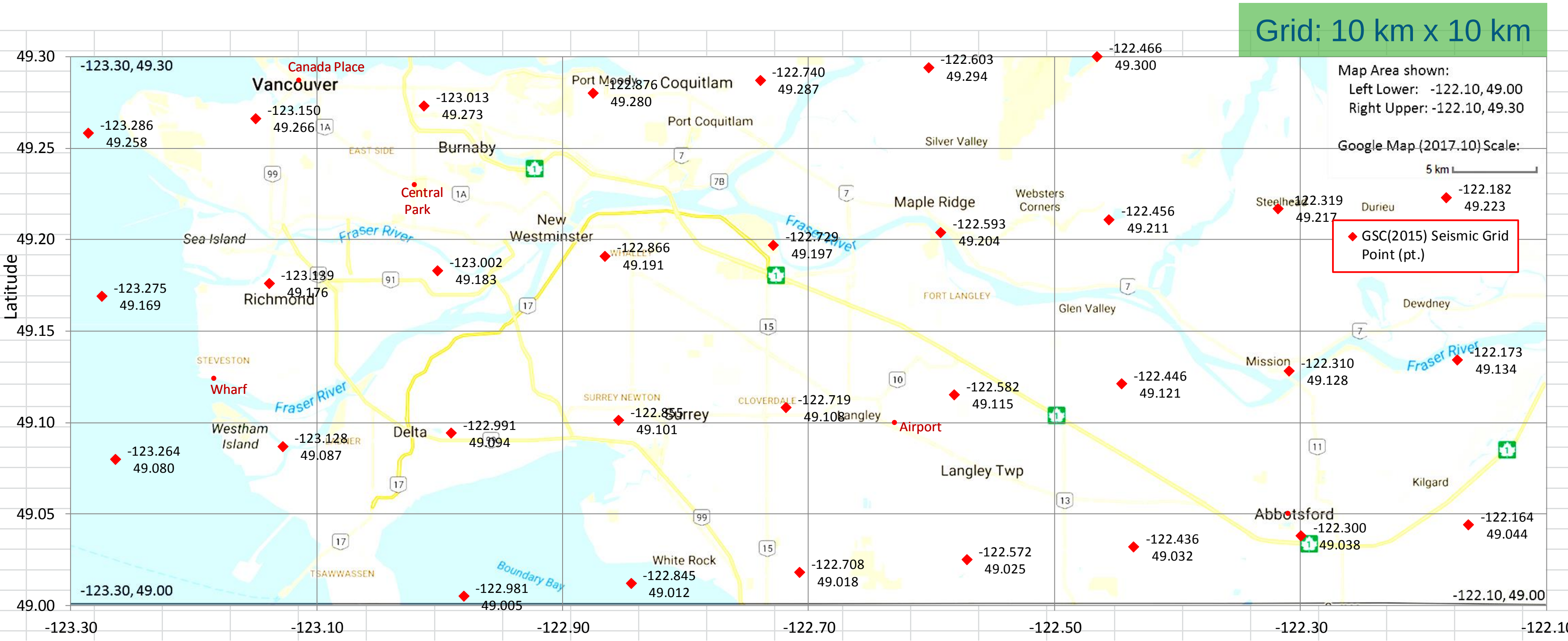
grid_files

- GSC_SWCan_All_PGA.txt
- GSC_SWCan_All_PGV.txt
- GSC_SWCan_All_Sa0.05.txt
- GSC_SWCan_All_Sa0.1.txt
- GSC_SWCan_All_Sa0.2.txt
- GSC_SWCan_All_Sa0.3.txt
- GSC_SWCan_All_Sa0.5.txt
- GSC_SWCan_All_Sa1.0.txt
- GSC_SWCan_All_Sa2.0.txt
- GSC_SWCan_All_Sa5.0.txt
- GSC_SWCan_All_Sa10.0.txt
- GSC_SWCan_Crust_PGA.txt
- GSC_SWCan_Crust_PGV.txt
- GSC_SWCan_Crust_Sa0.05.txt
- GSC_SWCan_Crust_Sa0.1.txt
- GSC_SWCan_Crust_Sa0.2.txt
- GSC_SWCan_Crust_Sa0.3.txt
- GSC_SWCan_Crust_Sa0.5.txt
- GSC_SWCan_Crust_Sa1.0.txt
- GSC_SWCan_Crust_Sa2.0.txt
- GSC_SWCan_Crust_Sa5.0.txt
- GSC_SWCan_Crust_Sa10.0.txt
- GSC_SWCan_Inslab_PGA.txt
- GSC_SWCan_Inslab_PGV.txt
- GSC_SWCan_Inslab_Sa0.05.txt
- GSC_SWCan_Inslab_Sa0.1.txt
- GSC_SWCan_Inslab_Sa0.2.txt
- GSC_SWCan_Inslab_Sa0.3.txt
- GSC_SWCan_Inslab_Sa0.5.txt
- GSC_SWCan_Inslab_Sa1.0.txt
- GSC_SWCan_Inslab_Sa2.0.txt
- GSC_SWCan_Inslab_Sa5.0.txt
- GSC_SWCan_Inslab_Sa10.0.txt
- GSC_SWCan_Interface_PGA.txt
- GSC_SWCan_Interface_PGV.txt
- GSC_SWCan_Interface_Sa0.05.txt
- GSC_SWCan_Interface_Sa0.1.txt
- GSC_SWCan_Interface_Sa0.2.txt
- GSC_SWCan_Interface_Sa0.3.txt
- GSC_SWCan_Interface_Sa0.5.txt
- GSC_SWCan_Interface_Sa1.0.txt
- GSC_SWCan_Interface_Sa2.0.txt
- GSC_SWCan_Interface_Sa5.0.txt
- GSC_SWCan_Interface_Sa10.0.txt

GSC Open File 8090

GSC (2015) fifth generation seismic hazard model

Seismic Grid Points in Greater Vancouver Region



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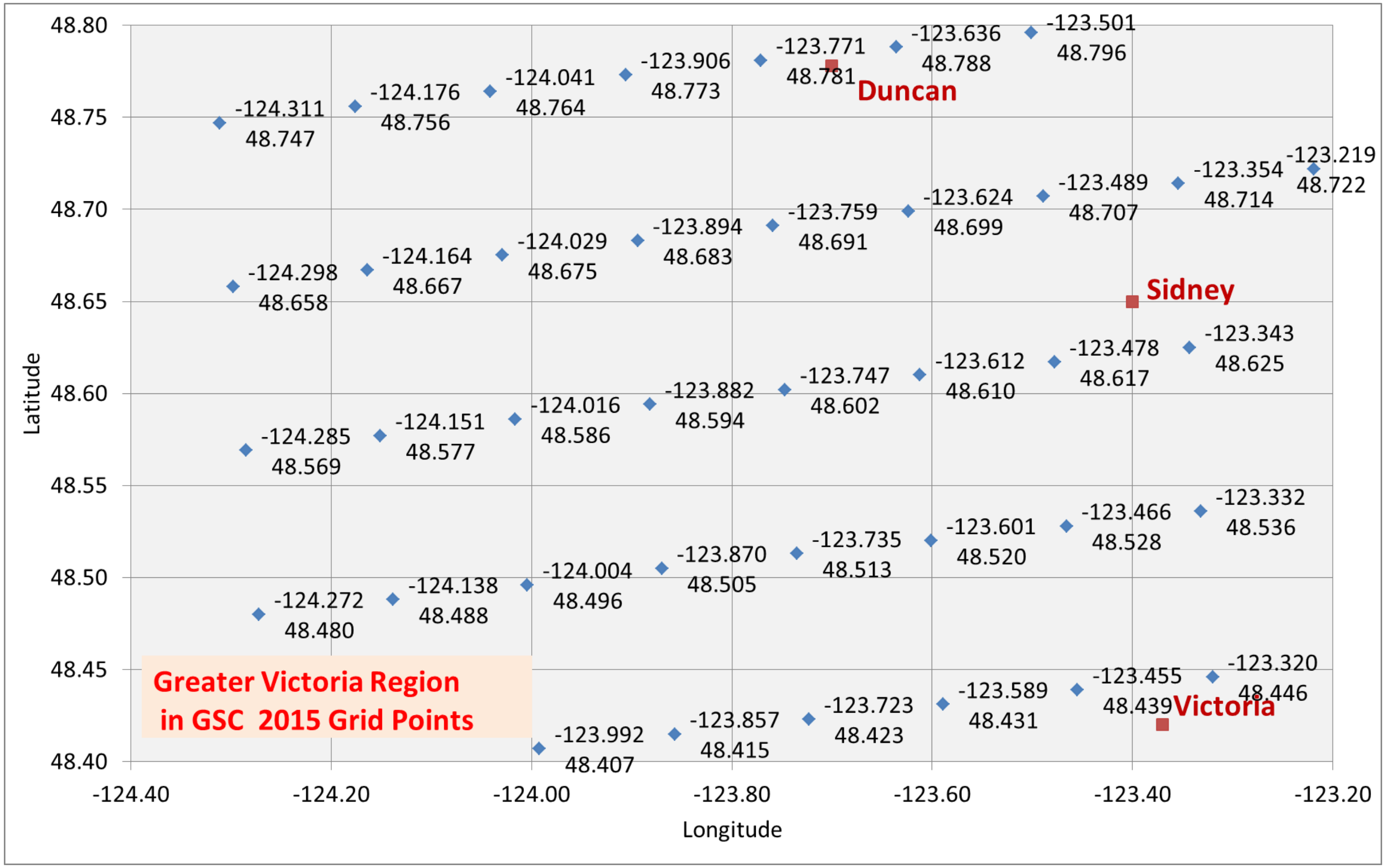
GSC (2015) fifth generation seismic hazard model

Seismic Grid Points in Greater Victoria Region



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	A	B	C	D	E	F	G	H	I	J	K	L	M
1	2015 GSC ALL SOURCES mean seismic hazard values									Excel file by Dr. G Wu (Sept 2017)			
2	ALL	Latitude	Longitude	0.02	0.01375	0.01	0.00445	0.0021	0.001	0.0005	0.000404	ALL	pt. No.
3	PGV	49.266	-123.15	0.0581	0.0776	0.0979	0.1691	0.2611	0.3762	0.5063	0.5517	pt.	34044
4	0.03	49.266	-123.15	0.052	0.0671	0.082	0.1297	0.1877	0.2594	0.3399	0.3676	pt.	34044
6	0.05	49.266	-123.15	0.0637	0.0815	0.0992	0.1555	0.2247	0.3128	0.4154	0.4509	pt.	34044
8	0.1	49.266	-123.15	0.0974	0.1246	0.1518	0.2388	0.3438	0.4766	0.6322	0.6854	pt.	34044
10	0.2	49.266	-123.15	0.1231	0.1576	0.1918	0.3019	0.4345	0.5984	0.7844	0.8468	pt.	34044
12	0.3	49.266	-123.15	0.1227	0.1575	0.1924	0.3053	0.4401	0.6056	0.7896	0.8508	pt.	34044
14	0.5	49.266	-123.15	0.0986	0.1285	0.1591	0.2592	0.3808	0.5289	0.6963	0.7539	pt.	34044
16	1	49.266	-123.15	0.0483	0.0638	0.0797	0.1342	0.2035	0.2918	0.3894	0.4248	pt.	34044
18	2	49.266	-123.15	0.0257	0.0342	0.0432	0.0746	0.1165	0.1719	0.2354	0.2566	pt.	34044
20	5	49.266	-123.15	0.0058	0.0076	0.0095	0.0166	0.0283	0.0475	0.0723	0.0808	pt.	34044
21	10	49.266	-123.15	0.0022	0.0028	0.0035	0.006	0.0099	0.0167	0.0255	0.0286	pt.	34044
22	Crustal			0.02	0.01375	0.01	0.00445	0.0021	0.001	0.0005	0.000404	Crustal	
23	PGV	49.266	-123.15	0.0194	0.0251	0.0308	0.0506	0.0778	0.1154	0.1645	0.183	pt.	34044
24	PGA	49.266	-123.15	0.0177	0.0244	0.0312	0.0546	0.0862	0.1301	0.1876	0.2096	pt.	34044
26	0.05	49.266	-123.15	0.0212	0.0292	0.0373	0.0656	0.1036	0.1569	0.229	0.2572	pt.	34044
28	0.1	49.266	-123.15	0.0317	0.0434	0.0552	0.0961	0.1511	0.2291	0.3351	0.3769	pt.	34044
30	0.2	49.266	-123.15	0.0442	0.0592	0.0746	0.1252	0.1917	0.2831	0.4014	0.4463	pt.	34044
32	0.3	49.266	-123.15	0.0452	0.0594	0.0738	0.1206	0.1812	0.2618	0.3638	0.402	pt.	34044
34	0.5	49.266	-123.15	0.0353	0.0461	0.0571	0.0936	0.1415	0.2053	0.2862	0.3163	pt.	34044
36	1	49.266	-123.15	0.0217	0.0279	0.0342	0.0551	0.0823	0.1186	0.164	0.1807	pt.	34044
38	2	49.266	-123.15	0.011	0.0139	0.0168	0.0266	0.0391	0.0557	0.0764	0.0839	pt.	34044
40	5	49.266	-123.15	0.0033	0.0041	0.005	0.0079	0.012	0.0173	0.0238	0.0262	pt.	34044
41	10	49.266	-123.15	0.0014	0.0017	0.0021	0.0033	0.0046	0.0064	0.0088	0.0097	pt.	34044
42	Inslab			0.02	0.01375	0.01	0.00445	0.0021	0.001	0.0005	0.000404	Inslab	
43	PGV	49.266	-123.15	0.042	0.057	0.073	0.1276	0.1984	0.2898	0.3946	0.4325	pt.	34044
44	PGA	49.266	-123.15	0.0398	0.0519	0.0643	0.1039	0.1528	0.2138	0.2832	0.3074	pt.	34044
46	0.05	49.266	-123.15	0.0496	0.0648	0.0798	0.1284	0.1889	0.2648	0.3496	0.3789	pt.	34044
48	0.1	49.266	-123.15	0.0772	0.1004	0.1232	0.1981	0.2912	0.4068	0.5355	0.5816	pt.	34044
50	0.2	49.266	-123.15	0.0962	0.1254	0.1547	0.2504	0.3679	0.515	0.6835	0.7412	pt.	34044
52	0.3	49.266	-123.15	0.096	0.1256	0.1556	0.2544	0.3758	0.5264	0.6982	0.7576	pt.	34044
54	0.5	49.266	-123.15	0.0759	0.1012	0.1267	0.2122	0.3196	0.4526	0.6035	0.6538	pt.	34044
56	1	49.266	-123.15	0.0317	0.0436	0.0557	0.0973	0.1493	0.2138	0.2872	0.3124	pt.	34044
58	2	49.266	-123.15	0.017	0.0237	0.0306	0.0534	0.0821	0.1172	0.1569	0.1707	pt.	34044
60	5	49.266	-123.15	0.0027	0.0037	0.0047	0.0083	0.0131	0.0186	0.0248	0.0268	pt.	34044
61	10	49.266	-123.15	0.0009	0.0012	0.0015	0.0027	0.0039	0.0054	0.0073	0.008	pt.	34044
62	Interface			0.02	0.01375	0.01	0.00445	0.0021	0.001	0.0005	0.000404	Interface	
63	PGV	49.266	-123.15	0.0007	0.0053	0.0112	0.0349	0.0914	0.1926	0.3114	0.348	pt.	34044
64	PGA	49.266	-123.15	0.0006	0.0013	0.0024	0.009	0.0306	0.0812	0.134	0.1499	pt.	34044
65	0.05	49.266	-123.15	0.0005	0.0011	0.0019	0.0076	0.0273	0.0761	0.1246	0.1409	pt.	34044
66	0.1	49.266	-123.15	0.0005	0.001	0.002	0.0102	0.0418	0.1231	0.2048	0.2316	pt.	34044
67	0.2	49.266	-123.15	0.0004	0.0011	0.0022	0.013	0.0548	0.1636	0.2721	0.3076	pt.	34044
68	0.3	49.266	-123.15	0.0005	0.0012	0.0025	0.0151	0.0644	0.1876	0.3135	0.3495	pt.	34044
69	0.5	49.266	-123.15	0.0006	0.0015	0.0034	0.0173	0.0693	0.1917	0.3224	0.3624	pt.	34044
70	1	49.266	-123.15	0.0006	0.0018	0.0038	0.0157	0.0566	0.1471	0.249	0.2815	pt.	34044
71	2	49.266	-123.15	0.0007	0.0019	0.0037	0.013	0.0423	0.1055	0.177	0.1989	pt.	34044
72	5	49.266	-123.15	0.0006	0.001	0.0017	0.0056	0.0162	0.0402	0.0673	0.0765	pt.	34044
73	10	49.266	-123.15	0.0003	0.0005	0.0007	0.0021	0.0057	0.0145	0.0243	0.0274	pt.	34044

GSC (2015) fifth generation seismic hazard model

Data from Open File 8090 for ALL-source, crustal, Inslab, and interface hazard values

- At 50-yr, 72-yr, 100-yr, 225-yr, 475-yr, 1000-yr, 2000-yr and 2475-yr
- At the Vancouver Grid Point No. 34044 (49.266 N; -123.15 W)
- One line from each of the 44 grid files to form this table

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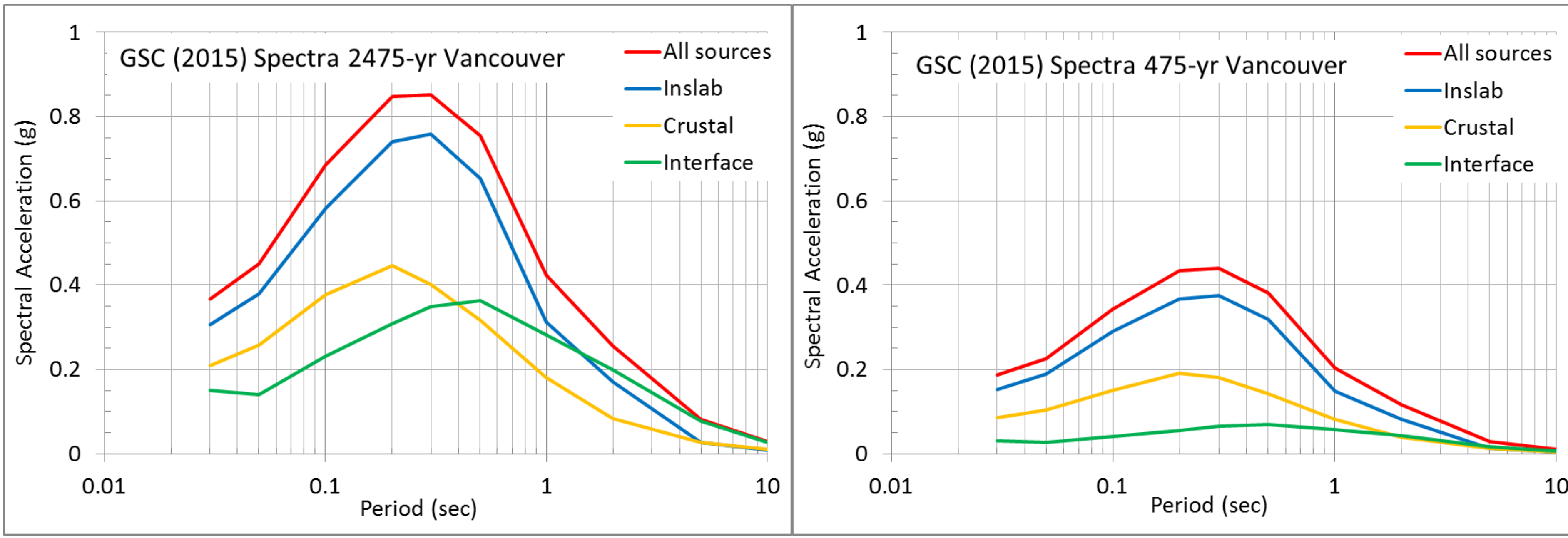
GSC (2015) fifth generation seismic hazard model

475-yr and 2475-yr UHS Curves for Vancouver Grid Point No. 34044 :

ALL-source, crustal, InSlab, and Interface hazard values



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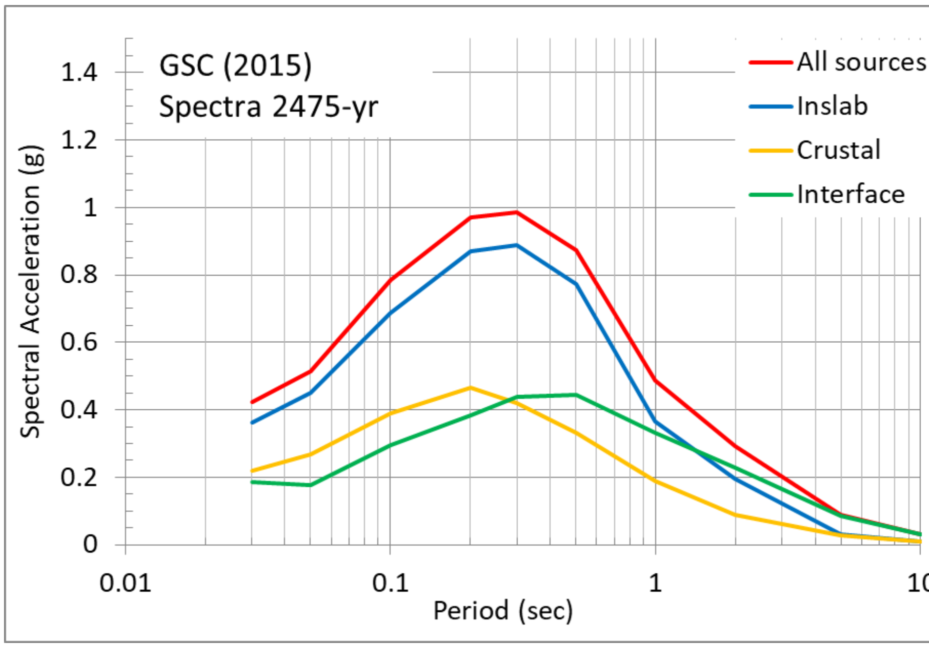
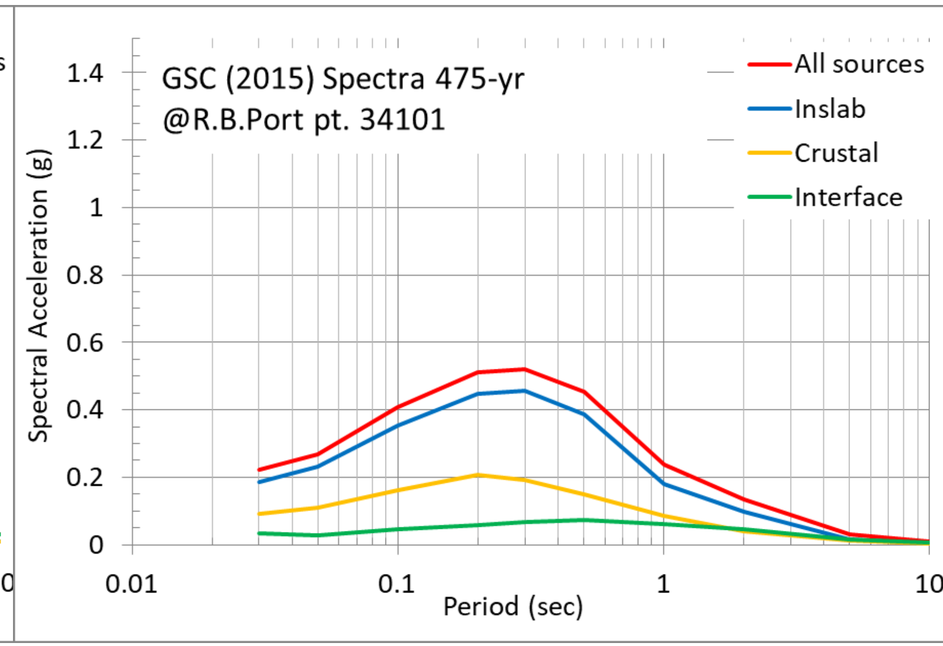
GSC (2015) fifth generation seismic hazard model

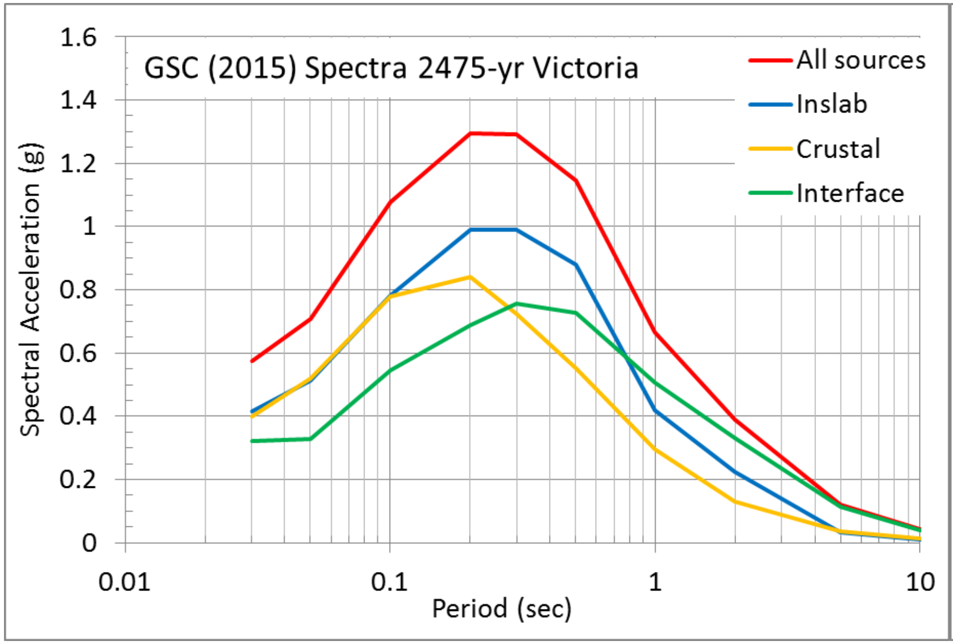
475-yr and 2475-yr UHS Curves for Grid Point No. 34101 (49.08 N; -123.264W) near GSC Borehole FD95-S1 at the Roberts Bank Port (150 m deep): ALL-source, crustal, InSlab, and Interface hazard values

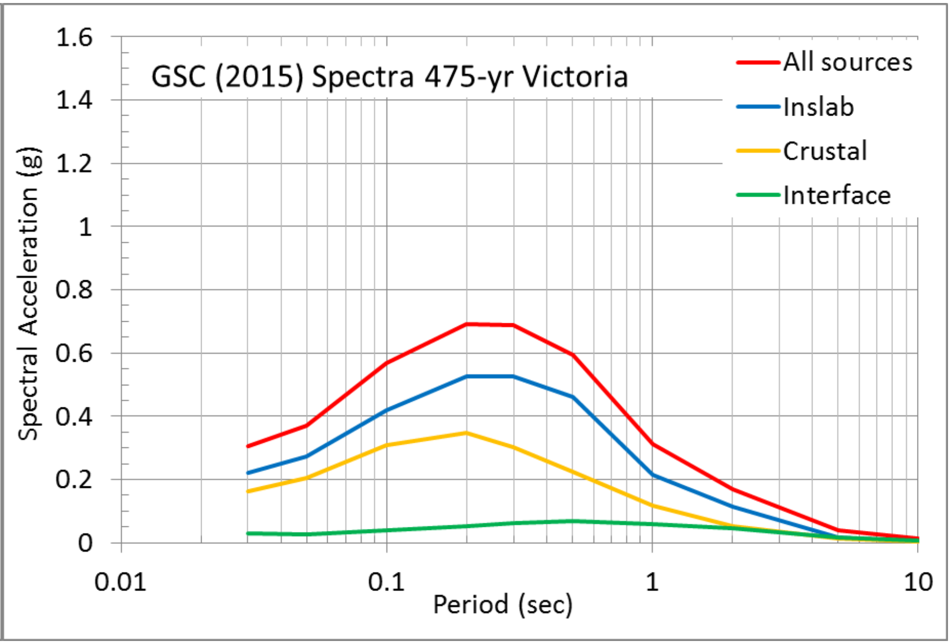




GSC (2015) fifth generation seismic hazard model

475-yr and 2475-yr UHS Curves for Grid Point No. 34310 (48.446N; -123.32W) in Victoria: ALL-source, crustal, InSlab, and Interface hazard values

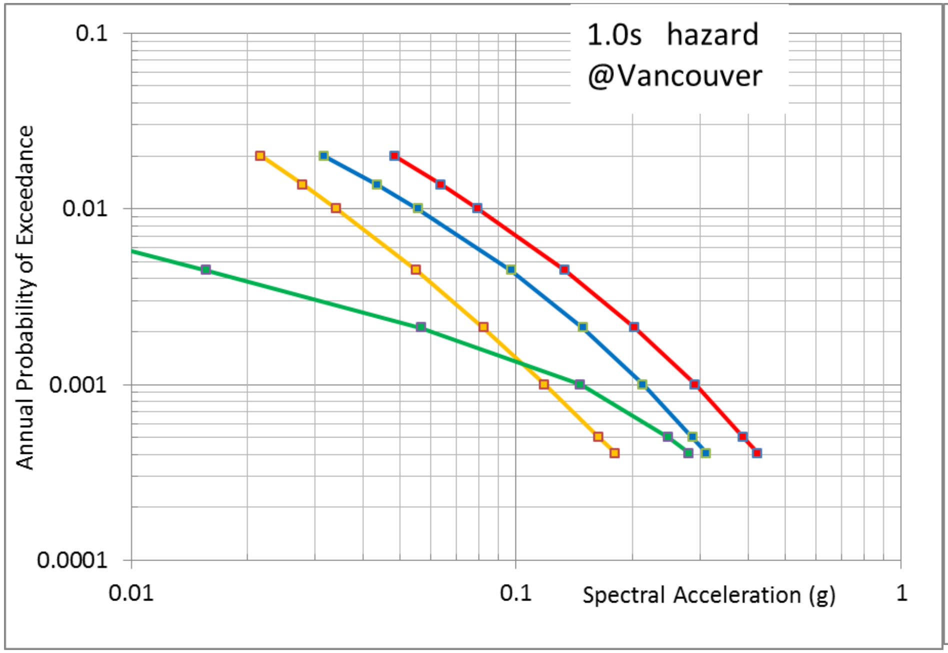


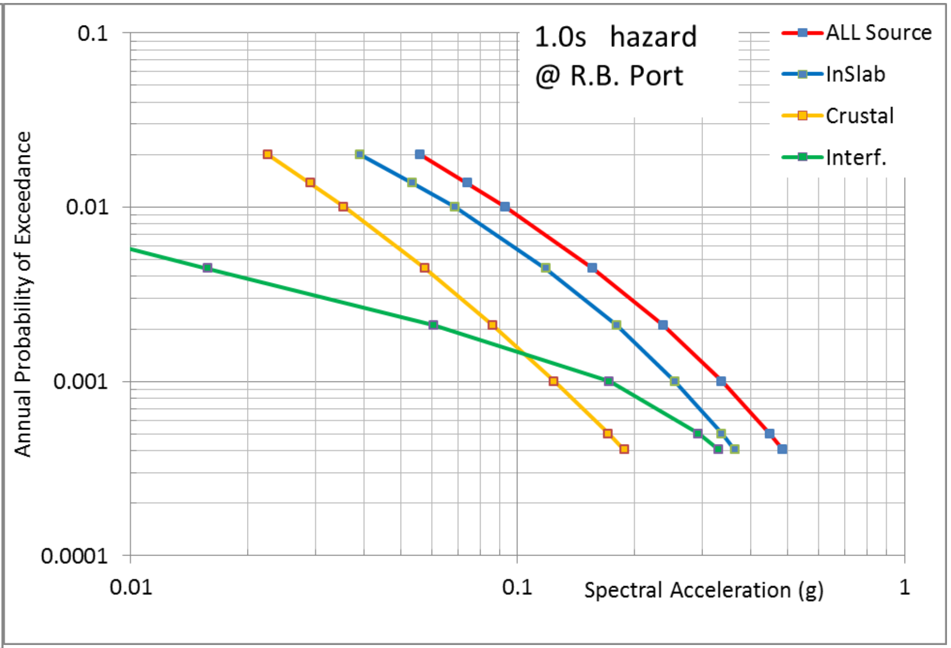


GSC (2015) fifth generation seismic hazard model

Acceleration Sa (1.0) Hazard Curves for the Vancouver site and the R.B. Port Site: ALL-source, crustal, InSlab, and Interface hazard values

(Note: Acce hazard curves for T=0.05, 0.1, 0.2, 0.3, 0.5, 2.0, 5.0, 10.0 s not shown)





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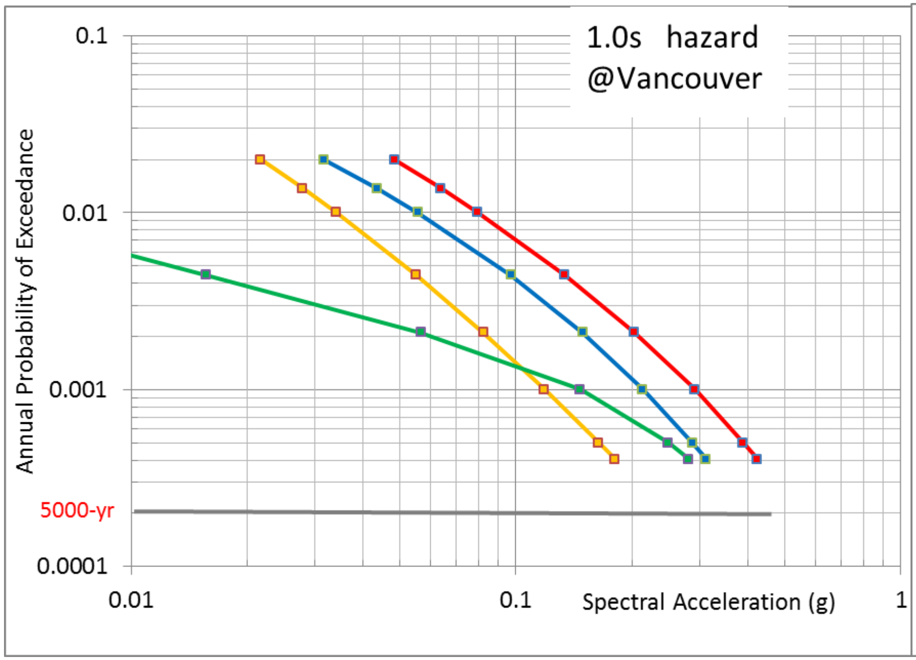
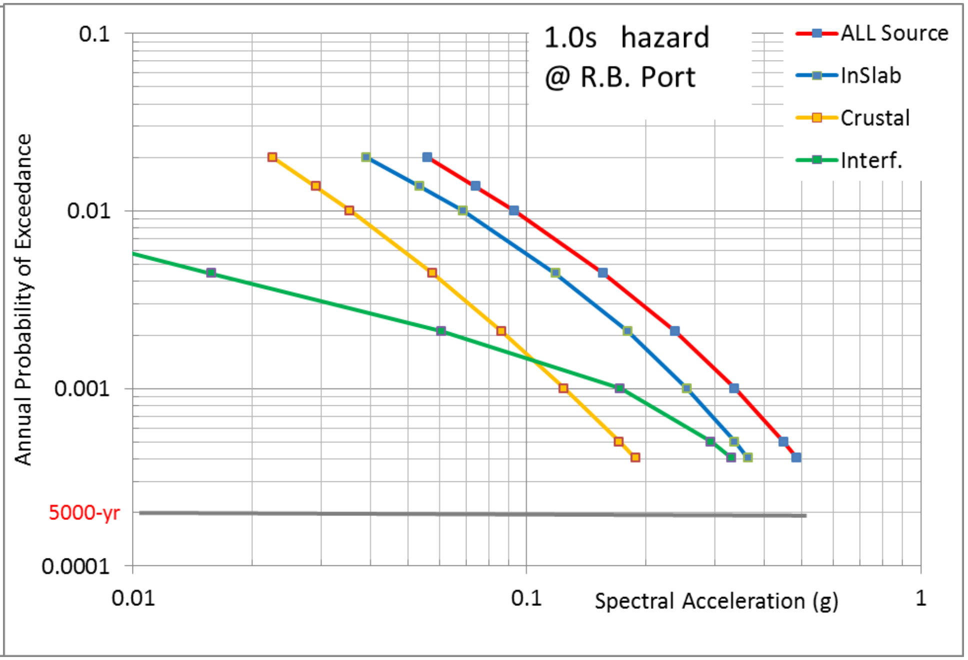
UHS for 5000-yr Level (1%/50 years) for: Subduction Interface and Inslab/Crustal

NOT required: ALL Source at 5000-yr;

Required by the probability approach: Interface and Inslab/Crustal at 5000-yr. How:

1. **Contact GSC for critical high impact projects: The individual source data at the 5000-yr level would be used when the 2475-yr ALL Source UHS values were calculated by GSC; or**
2. **Use the below proposed method by extrapolating the InSlab/Crustal curve to 5000-yr and back-calculating 5000-yr values for Interface. Note: InSlab/Crustal curves are more suitable for extrapolation!**





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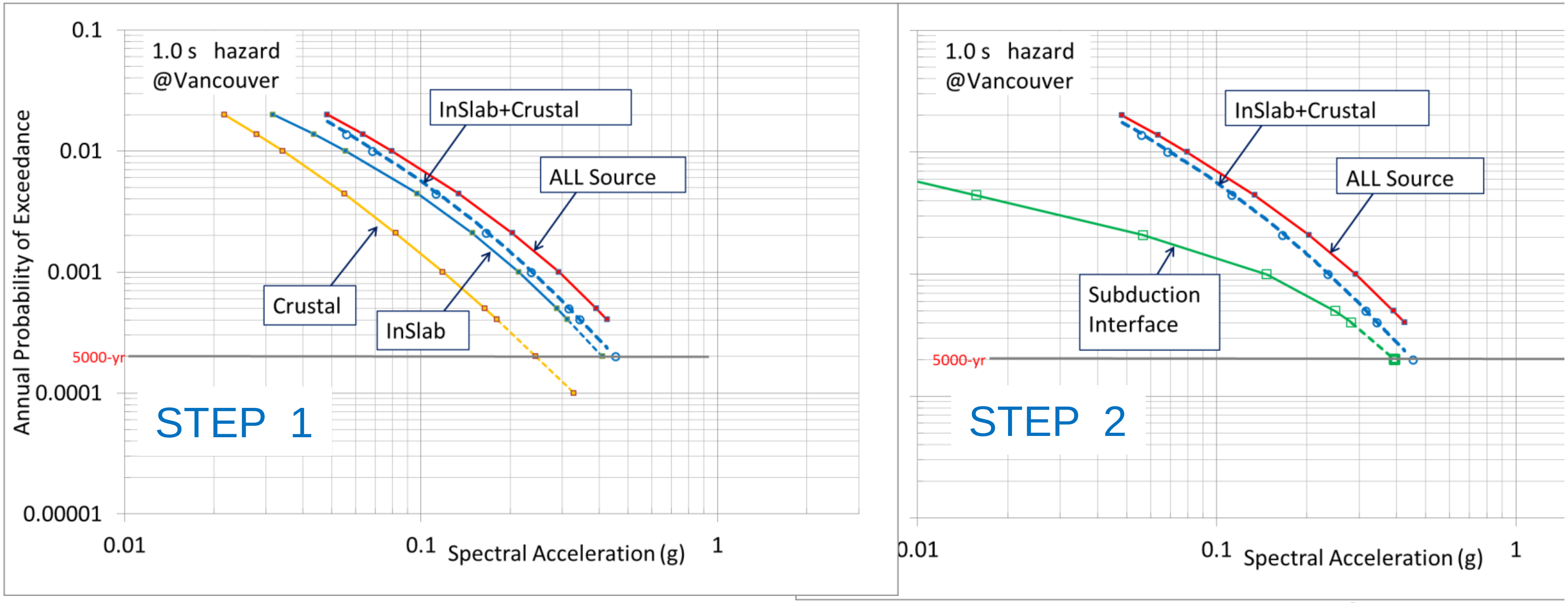
UHS for 5000-yr Level (1%/50 years) for: Subduction Interface and Inslab/Crustal

1. Extend the InSlab and Crustal curves beyond the 2475-yr level on the Log-Log scale;
2. Add probability of InSlab and Crustal points at a given period (e.g. 1.0 s) which will result in the combined InSlab/Crustal hazard curve, see below STEP 1; and
3. Subtract probability of the ALL Source by the InSlab/Crustal points, also for the period of 1.0 s, for the portion of the Subduction Interface curve from 2475-yr to 5000-yr level.
4. DO NOT ADD Sa Values at a given probability level - This is why we have to carry out the Probability Approach.



UHS for 5000-yr Level (1%/50 years) for: Subduction Interface and Inslab/Crustal

The calculations are coded in an Excel file so the 5000-yr UHS and the 10,000-yr UHS (if required for analysis, likely, for InSlab/Crustal source) can be auto-generated and plotted.

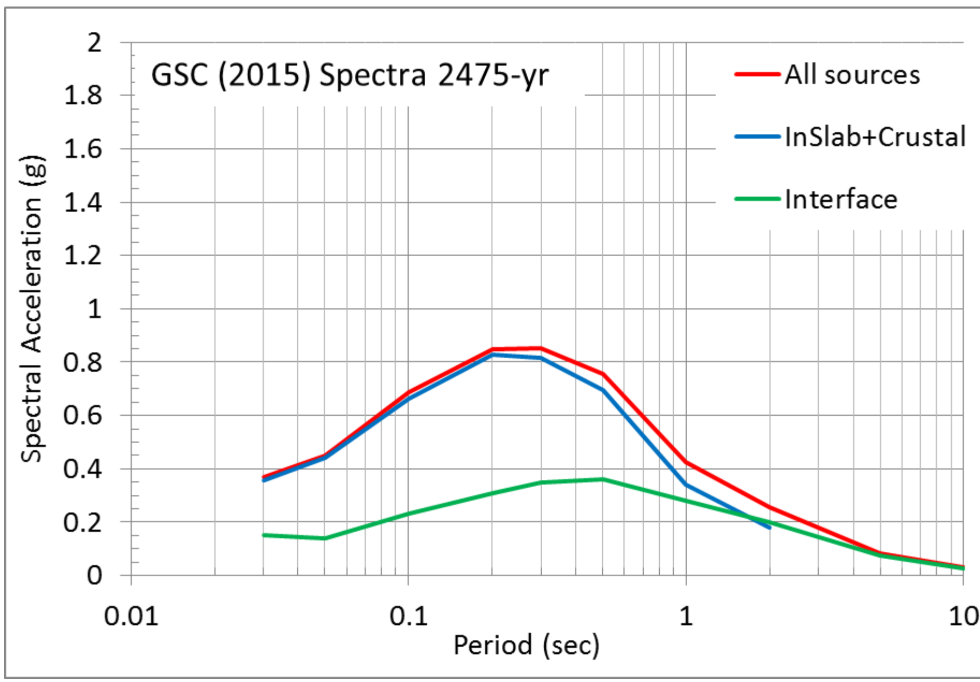
	A	B	C	D	E	F	G	H	I	J	K	N	O	P
1	2015 GSC ALL SOURCES mean seismic hazard values. PGA or Sa(T) on Soil Class C (Vs30 = 450 m/s) for probabilities of 1/50 - 1/2475 years.													
2	**ALL**	Latitude	Longitude	0.02	0.01375	0.01	0.00445	0.0021	0.001	0.0005	0.000404			
3	PGV	49.266	-123.15	0.0581	0.0776	0.0979	0.1691	0.2611	0.3762	0.5063	0.5517			ru
4	0.03	49.266	-123.15	0.052	0.0671	0.082	0.1297	0.1877	0.2594	0.3399	0.3676			
6	0.05	49.266	-123.15	0.0637	0.0815	0.0992	0.1555	0.2247	0.3128	0.4154	0.4509			
8	0.1	49.266	-123.15	0.0974	0.1246	0.1518	0.2388	0.3438	0.4766	0.6322	0.6854			
10	0.2	49.266	-123.15	0.1231	0.1576	0.1918	0.3019	0.4345	0.5984	0.7844	0.8468			
12	0.3	49.266	-123.15	0.1227	0.1575	0.1924	0.3053	0.4401	0.6056	0.7896	0.8508			
14	0.5	49.266	-123.15	0.0986	0.1285	0.1591	0.2592	0.3808	0.5289	0.6963	0.7539			
16	1	49.266	-123.15	0.0483	0.0638	0.0797	0.1342	0.2035	0.2918	0.3894	0.4248			
18	2	49.266	-123.15	0.0257	0.0342	0.0432	0.0746	0.1165	0.1719	0.2354	0.2566			
20	5	49.266	-123.15	0.0058	0.0076	0.0095	0.0166	0.0283	0.0475	0.0723	0.0808			
21	10	49.266	-123.15	0.0022	0.0028	0.0035	0.006	0.0099	0.0167	0.0255	0.0286			
62	**Interface**			0.02	0.01375	0.01	0.00445	0.0021	0.001	0.0005	0.000404	0.0002	0.0001	
63	PGV	49.266	-123.15	0.0007	0.0053	0.0112	0.0349	0.0914	0.1926	0.3114	0.348	0.0198	0.0199	
64	PGA	49.266	-123.15	0.0006	0.0013	0.0024	0.009	0.0306	0.0812	0.134	0.1499	0.2020	0.2691	
65	0.05	49.266	-123.15	0.0005	0.0011	0.0019	0.0076	0.0273	0.0761	0.1246	0.1409	0.1832	0.2458	
66	0.1	49.266	-123.15	0.0005	0.001	0.002	0.0102	0.0418	0.1231	0.2048	0.2316	0.3018	0.3863	
67	0.2	49.266	-123.15	0.0004	0.0011	0.0022	0.013	0.0548	0.1636	0.2721	0.3076	0.4411	0.5722	
68	0.3	49.266	-123.15	0.0005	0.0012	0.0025	0.0151	0.0644	0.1876	0.3135	0.3495	0.4931	0.6498	
69	0.5	49.266	-123.15	0.0006	0.0015	0.0034	0.0173	0.0693	0.1917	0.3224	0.3624	0.5052	0.6695	
70	1	49.266	-123.15	0.0006	0.0018	0.0038	0.0157	0.0566	0.1471	0.249	0.2815	0.3929	0.5318	
71	2	49.266	-123.15	0.0007	0.0019	0.0037	0.013	0.0423	0.1055	0.177	0.1989	0.2761	0.3691	
72	5	49.266	-123.15	0.0006	0.001	0.0017	0.0056	0.0162	0.0402	0.0673	0.0765	nterface dominates		
73	10	49.266	-123.15	0.0003	0.0005	0.0007	0.0021	0.0057	0.0145	0.0243	0.0274	for T=3 - 10 sec		
74														
75	**InSlab_Crustal - interpolated by vlookup:**				0.01375	0.01	0.00445	0.0021	0.001	0.0005	0.000404	0.0002	0.0001	
76	PGV				0.0063	0.0100	0.0156	0.0179	0.0190	0.0195	0.0196	0.0198	0.0199	
77	PGA				0.0626	0.0760	0.1202	0.1732	0.2451	0.3270	0.3565	0.4722	0.6227	
78	0.05				0.0762	0.0939	0.1471	0.2143	0.3022	0.4031	0.4403	0.5838	0.7702	
79	0.1				0.1164	0.1409	0.2258	0.3281	0.4607	0.6135	0.6641	0.8845	1.1650	
80	0.2				0.1473	0.1781	0.2799	0.4080	0.5722	0.7621	0.8281	1.0891	1.4259	
81	0.3				0.1471	0.1784	0.2827	0.4064	0.5659	0.7528	0.8141	1.0710	1.3934	
82	0.5				0.1165	0.1438	0.2342	0.3443	0.4815	0.6427	0.6963	0.9138	1.1906	
83	1				0.0561	0.0686	0.1124	0.1654	0.2353	0.3152	0.3426	0.4532	0.5950	
84	2				0.0300	0.0360	0.0589	0.0893	0.1254	0.1675	0.1795	0.2375	0.3118	
85	5				Interface dominates for T=3 to 10 sec							Values extrapolated!		
86														
87														
88		NOTES:	Data in Rows 1 to 73, Columns A to K are extracted from GSC(2015) OPEN FILE 8090											
89			All others are interpretations by Dr. G. Wu in September 2017											
90														
91		GSC (2015) for Vancouver												

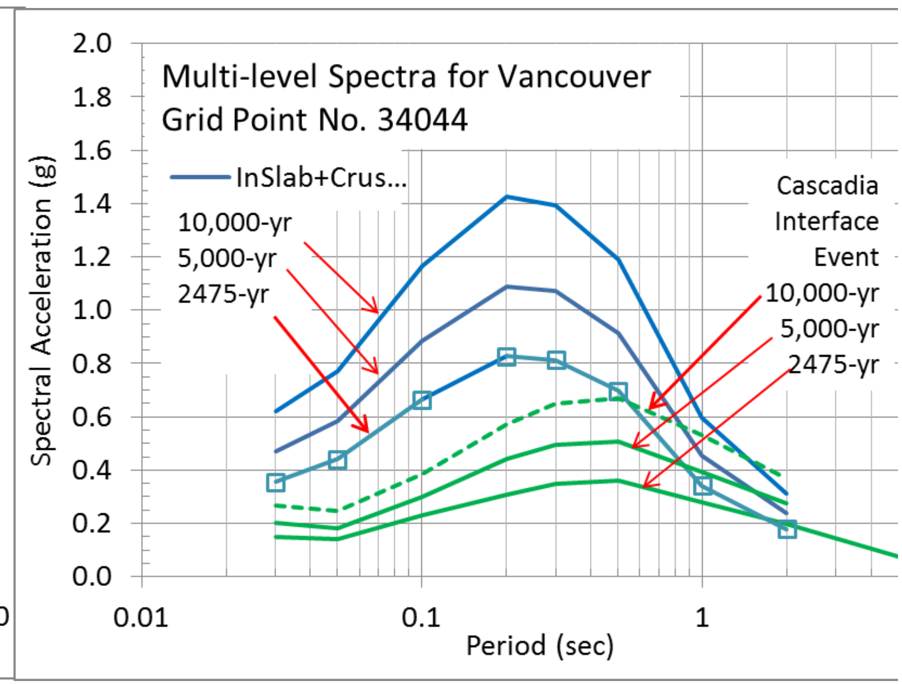
UHS for 5000-yr Level (1%/50 years), and 10,000-yr when required

For Vancouver Grid Point No. 34044:

Subduction Interface and InSlab/Crustal ONLY

Note: Contact GSC if 10,000-yr Interface UHS (dash line) has a major impact to the analysis results.





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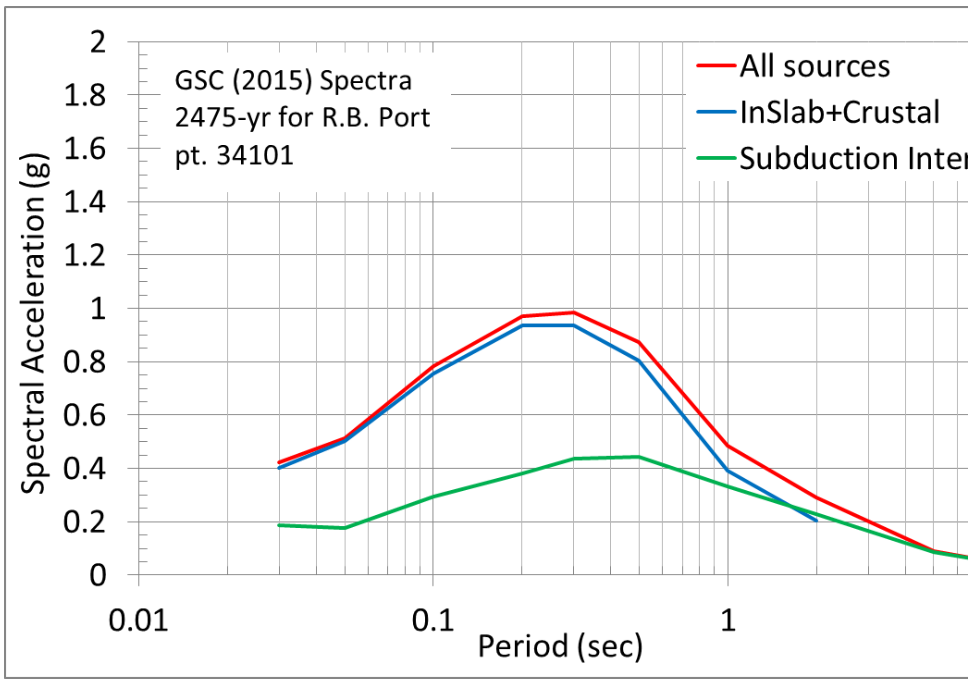
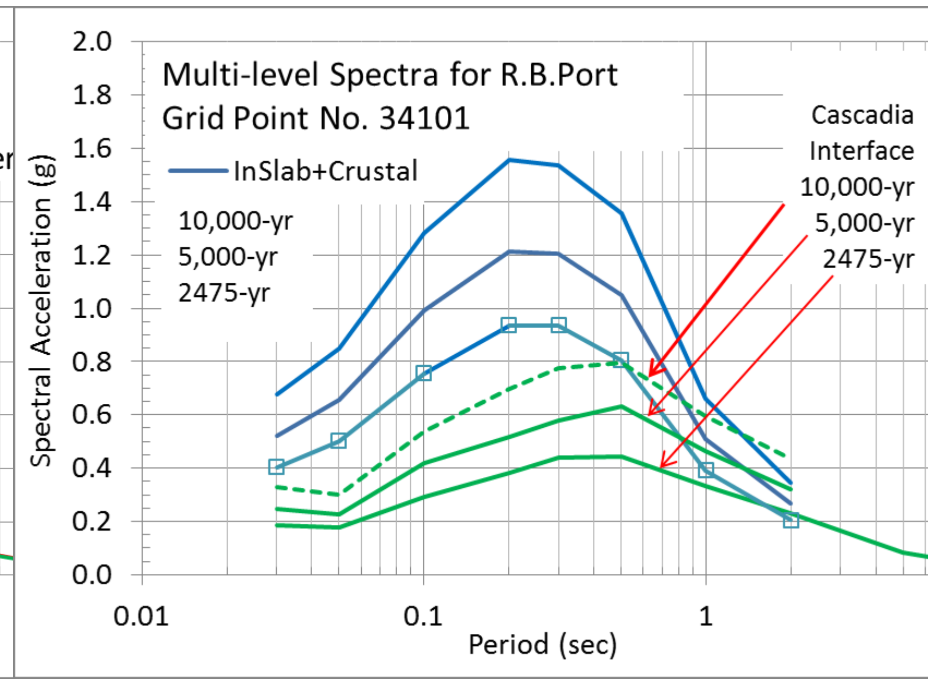
UHS for 5000-yr Level (1%/50 years), and 10,000-yr when required

Grid Point No. 34101 (49.08 N; -123.264W) near GSC Borehole FD95-S1 at the Roberts Bank Port (150 m deep): Subduction Interface and InSlab/Crustal ONLY

Note: Contact GSC if 10,000-yr Interface UHS (dash line) has a major impact to the analysis results





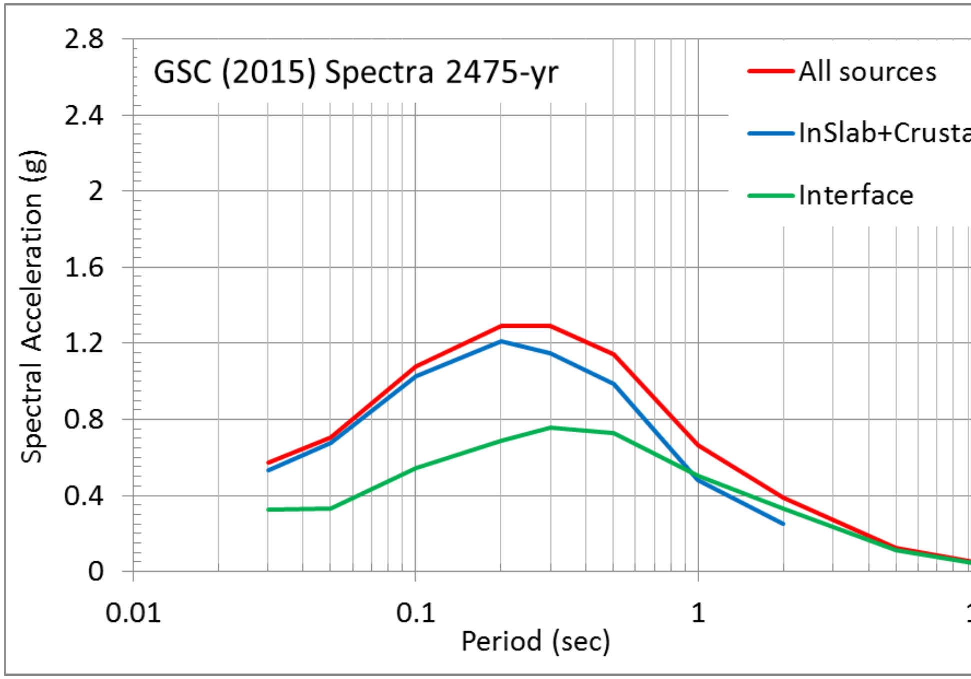
BC Hydro
Power smart

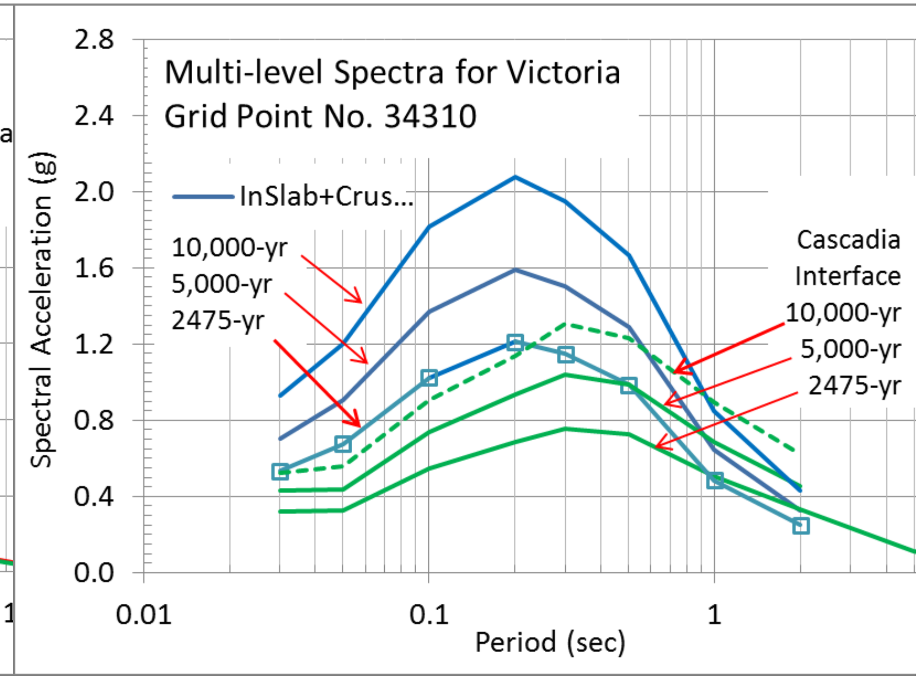
UHS for 5000-yr Level (1%/50 years), and 10,000-yr when required

For Victoria Grid Point No. 34310:

Subduction Interface and InSlab/Crustal ONLY

Note: Contact GSC if 10,000-yr Interface UHS (dash line) has a major impact to the analysis results





Seismic Slope Displacements for a Probability of 2%/50 years

- **Empirical equations by Bray and Travasarou (2007) for InSlab/Crustal Source, and by Macedo et al (2017) for Subduction Earthquake Source;**
- **Using spectral acce. Values, Sa(1.5Ts), from the individual UHS curves for the two earthquake sources: InSlab/Crustal and Subduction Interface**

For InSlab/Crustal (M~7) Source from Bray and Travasarou (2007) :

Probability for Zero-displacemen (D) using Eq. [3]:

$$P(D=0) = 1 - \Phi(-1.76 - 3.22\ln(k_y) - 0.484T_s\ln(k_y) + 3.52\ln(S_a(1.5T_s))) \quad (3)$$

Nonzero seismic displacement (D) for Ts>0.05 s is estimated using Eq. [5]:

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

Net probability of nonzero disp. (D) using Eq. (7):

$$P(D>d) = [1 - P(D=0)]P(D>d|D>0) \quad (7)$$

Seismic Slope Displacements for a Probability of 2%/50 years

For Subduction Interface (M~9) Source from Macedo et al (2017) **:**

Probability for Zero-displacement (D) using Eq. (2) or (3) below:

For $Ts \leq 0.7$ sec.

$$P(D=0) = 1 - \Phi\left(-2.75 - 3.3Ln(k_y) - 0.18\left(Ln(k_y)\right)^2 - 0.56TsLn(k_y) + 1.94T_s + 2.95Ln(Sa(1.5T_s))\right) \quad (2)$$

For $Ts > 0.7$ sec.

$$P(D=0) = 1 - \Phi\left(-3.77 - 5.17Ln(k_y) - 0.40\left(Ln(k_y)\right)^2 - 0.43TsLn(k_y) - 1.03T_s + 2.91Ln(Sa(1.5T_s))\right) \quad (3)$$

Nonzero seismic displacement (D) for Ts>0.05 s is estimated using Eq. [4]:

$$Ln(D) = -6.97 - 3.045Ln(k_y) - 0.328\left(Ln(k_y)\right)^2 + 0.448Ln(k_y)Ln(Sa(1.5T_s)) + 2.605Ln(Sa(1.5T_s)) - 0.233\left(Ln(Sa(1.5T_s))\right)^2 + 1.407T_s + 0.643M \pm \varepsilon \quad (4)$$

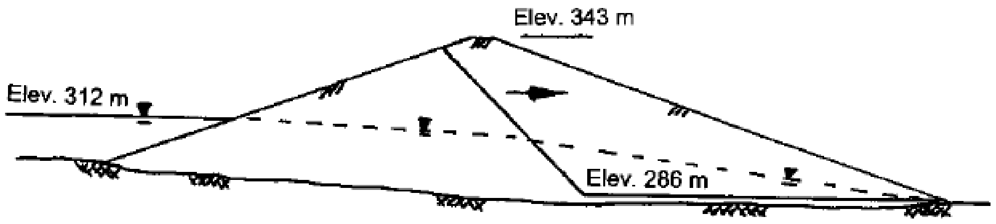
Net probability of nonzero disp. (D) using Eq. (6):

$$P(D>d) = [1-P(D=0)] \cdot P(D>d|D>0) \quad (6)$$

Seismic Slope Displacements for a Probability of 2%/50 years

Input parameters used in below examples are:

- Yield acceleration coefficient ky = 0.13
- Initial period of the sliding mass: Ts = 0.33s and 0.67s
- M_InSlab/Crust =7.0; or
- M_subduction-interface= 9.0
- Sa(1.5Ts) = from UHS curves (1000-yr, 2475-yr, 5000-yr, etc), or interpolated in between the curves, for subduction-interface source or for InSlab/Crustal source at a probability level (P) - a total of 100 probability (P) points from 0.001 to 0.0001.



Example cross section of dam with downstream slope potential sliding mass evaluated for seismic displacements: D = f (Prob.) Source: Figure 10 of Bray and Travasarou (2007)

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Seismic Slope Displacements for a Probability of 2%/50 years

Example 1: For a site located at Vancouver Grid Point No. 34044: Ts=0.33 sec

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	**Bray and Trovasarou (2007) and Mecedo et al (2017) Displacements by Dr. G Wu (2017.10)**															
2									**Input parameters:**							
3	Semi-Log SLOPE for spectrum curves						yield acce coe. ky =		0.13							
4	for 1000-yr, 2475-yr, 5000-yr, and 10,000-yr						initial Period: Ts =		0.33	**0.495**	for 1.5*Ts					
5	**Table 1 and 2 below use data from "GSC(2015) OPEN FILE 8090"**						M_InSlab+Crust =		7.0							
6	vLookup Table 1						M_interface=		9.0							
7	T (s)	**SLOPEs - Interface**														
8	0.0500	0.1561	0.301299	0.394047	0.466571			vLookup Table 3 Log-log Slope in Prob() ~ Sa curves						Bray's Disp. (Crustal and Subduction)		
9	0.1000	0.1345	0.252467	0.462598	0.61748			Prob()	InSlab+Cru	*log-log Slope*	Interface	*log-log Slope*		InSlab+Crust	Interface	ALL Source
10	0.2000	0.1363	0.237945	0.295324	0.44059		*Sa()_10000*	0.0001	1.1946	*-0.39166*	0.6691	*-0.40610*		(to update below displacement values		
11	0.3000	0.0185	0.058148	0.05474	0.089052		*Sa()_5000*	0.0002	0.9169	*-0.39669*	0.5050	*-0.47282*		37.30	17.20	
12	0.5000	-0.1482	-0.26874	-0.37293	-0.45751		*Sa()_2475*	0.000404	0.6986	*-0.40684*	0.3621	*-0.70232*				28.21
13	1.0000	-0.1382	-0.27439	-0.38805	-0.54043		*Sa()_1000*	0.001	0.4832	*0.00000*	0.1916	*0.00000*				
14	2.0000	0	0	0	0											
15							*InSlab+Crustal Prob(D>d|D>0)*			**P1**	*Interface Prob(D>d|D>0)*			**P2**	**P = P1 + P2 at D (cm)**	
16	vLookup Table 2					**Prob(D>d|D>0)**	Sa(InSlab+	ln(D)	D (cm) ε=0	Prob(D>d)	Sa(Interface)	ln(D)	D (cm) ε=0	Prob(D>d)	Prob-TOTAL	No.
17	T (s)	**SLOPEs (InSlab+Crustal)**				0.001000	0.4832	2.282	9.80	0.000995	0.1916	0.698	2.01	0.000267	0.001329	0
18	0.0500	0.5263	0.74368	0.998871	1.311451	0.000977	0.4877	2.303	10.01	0.000973	0.1947	0.738	2.09	0.000276	0.001301	1
19	0.1000	0.3704	0.544663	0.679708	0.866625	0.000955	0.4923	2.324	10.22	0.000951	0.1979	0.778	2.18	0.000285	0.001279	2
20	0.2000	-0.0358	-0.0795	-0.10274	-0.18451	0.000933	0.4969	2.345	10.43	0.000930	0.2011	0.817	2.26	0.000294	0.001252	3
21	0.3000	-0.3803	-0.5309	-0.70867	-0.91434	0.000912	0.5016	2.366	10.65	0.000909	0.2044	0.857	2.36	0.000303	0.001225	4
22	0.5000	-0.8179	-1.17513	-1.5301	-1.97839	0.000891	0.5063	2.387	10.88	0.000889	0.2078	0.896	2.45	0.000312	0.001199	5
23	1.0000	-0.3652	-0.54158	-0.71643	-0.94078	0.000871	0.5111	2.407	11.11	0.000869	0.2111	0.935	2.55	0.000321	0.001173	6
24	2.0000	0	0	0	0	0.000851	0.5159	2.428	11.34	0.000849	0.2146	0.974	2.65	0.000329	0.001148	7
25						0.000832	0.5208	2.449	11.57	0.000830	0.2181	1.013	2.75	0.000336	0.001123	8
26						0.000813	0.5257	2.469	11.82	0.000811	0.2216	1.052	2.86	0.000344	0.001099	9
27						0.000794	0.5306	2.490	12.06	0.000793	0.2253	1.090	2.98	0.000351	0.001075	10
28						0.000776	0.5356	2.511	12.31	0.000775	0.2289	1.129	3.09	0.000358	0.001051	11
29						0.000759	0.5407	2.531	12.57	0.000757	0.2327	1.167	3.21	0.000364	0.001034	12
30						0.000741	0.5457	2.552	12.83	0.000740	0.2365	1.206	3.34	0.000370	0.001011	13

Seismic Slope Displacements for a Probability of 2%/50 years

	InSlab+Crustal Prob(D>d|D>0)			P1	Interface Prob(D>d|D>0)			P2	P = P1 + P2 at D (cm)	
Prob(D>d|D>0)	Sa(InSlab+	ln(D)	D (cm) ε=0	Prob(D>d)	Sa(Interface)	ln(D)	D (cm) ε=0	Prob(D>d)	Prob-TOTAL	No.
0.000347	0.7412	3.196	24.44	0.000347	0.3893	2.326	10.23	0.000322	0.000481	46
0.000339	0.7478	3.214	24.88	0.000339	0.3935	2.349	10.47	0.000316	0.000470	47
0.000331	0.7545	3.232	25.34	0.000331	0.3979	2.372	10.72	0.000310	0.000460	48
0.000324	0.7612	3.250	25.80	0.000324	0.4022	2.395	10.97	0.000305	0.000449	49
0.000316	0.7680	3.268	26.26	0.000316	0.4066	2.418	11.22	0.000299	0.000439	50
0.000309	0.7749	3.286	26.74	0.000309	0.4111	2.441	11.49	0.000293	0.000429	51
0.000302	0.7818	3.304	27.22	0.000302	0.4156	2.464	11.75	0.000287	0.000419	52
0.000295	0.7888	3.322	27.71	0.000295	0.4201	2.487	12.02	0.000282	0.000410	53
0.000288	0.7959	3.340	28.21	0.000288	0.4247	2.510	12.30	0.000276	0.000400	54
0.000282	0.8030	3.357	28.71	0.000282	0.4294	2.532	12.58	0.000271	0.000391	55
0.000275	0.8102	3.375	29.23	0.000275	0.4341	2.555	12.87	0.000265	0.000382	56
0.000269	0.8174	3.393	29.75	0.000269	0.4388	2.578	13.17	0.000260	0.000374	57
...	...	...	...	...	...	...	...	...	...	...
0.000214	0.8935	3.567	35.42	0.000214	0.4893	2.801	16.46	0.000210	#VALUE!	67
0.000209	0.9015	3.585	36.04	0.000209	0.4946	2.823	16.82	0.000206	#VALUE!	68
0.000204	0.9096	3.602	36.67	0.000204	0.5001	2.845	17.20	0.000201	#VALUE!	69
0.000200	0.9177	3.619	37.30	0.000200	0.5055	2.866	17.57	0.000197	#VALUE!	70
0.000195	0.9258	3.636	37.94	0.000195	0.5102	2.885	17.90	0.000193	#VALUE!	71
0.000191	0.9340	3.653	38.58	0.000191	0.5150	2.904	18.24	0.000188	#VALUE!	72
...	...	...	...	...	...	...	...	...	...	...
0.000141	1.0470	3.869	47.89	0.000141	0.5816	3.143	23.18	0.000141	#VALUE!	85
0.000138	1.0563	3.885	48.68	0.000138	0.5870	3.162	23.61	0.000138	#VALUE!	86
0.000135	1.0656	3.901	49.48	0.000135	0.5925	3.180	24.04	0.000134	#VALUE!	87
0.000132	1.0750	3.918	50.29	0.000132	0.5981	3.198	24.48	0.000131	#VALUE!	88
0.000129	1.0845	3.934	51.11	0.000129	0.6037	3.216	24.92	0.000128	#VALUE!	89
0.000126	1.0941	3.950	51.95	0.000126	0.6094	3.234	25.38	0.000126	#VALUE!	90
0.000123	1.1037	3.966	52.79	0.000123	0.6151	3.252	25.84	0.000123	#VALUE!	91
...	...	...	...	...	...	...	...	...	...	...
0.000120	1.1135	3.982	53.65	0.000120	0.6209	3.270	26.30	0.000120	#VALUE!	92
0.000117	1.1233	3.999	54.52	0.000117	0.6267	3.288	26.78	0.000117	#VALUE!	93
0.000115	1.1332	4.015	55.40	0.000115	0.6326	3.305	27.26	0.000115	#VALUE!	94
0.000112	1.1432	4.031	56.30	0.000112	0.6386	3.323	27.75	0.000112	#VALUE!	95
0.000110	1.1533	4.047	57.20	0.000110	0.6446	3.341	28.24	0.000109	#VALUE!	96

Legend:
Red - ALL Source
Green - Interface
Blue – InSlab/Crustal

Vancouver Grid Point No. 34044 Ts=0.33 sec
At 28.21 cm,
P1 = 0.0002884
P2 = 0.0001095

*using VLOOKUP in Excel:
P = P1 + P2
~= 0.000400

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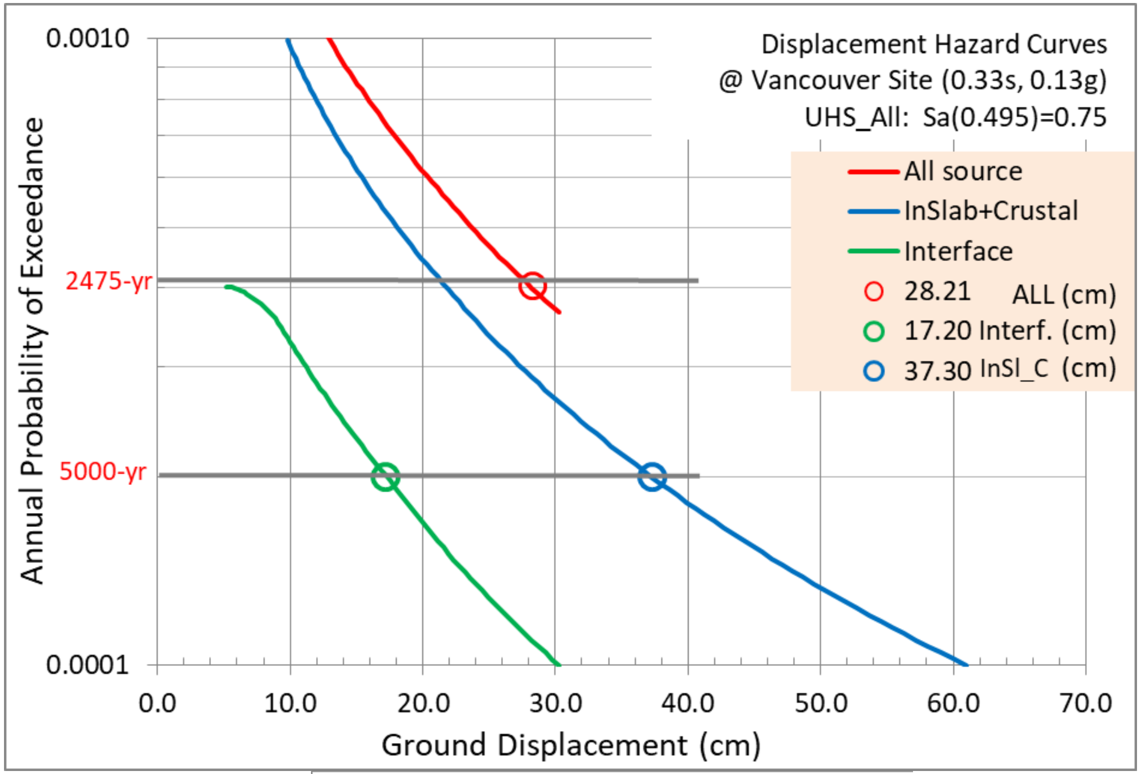
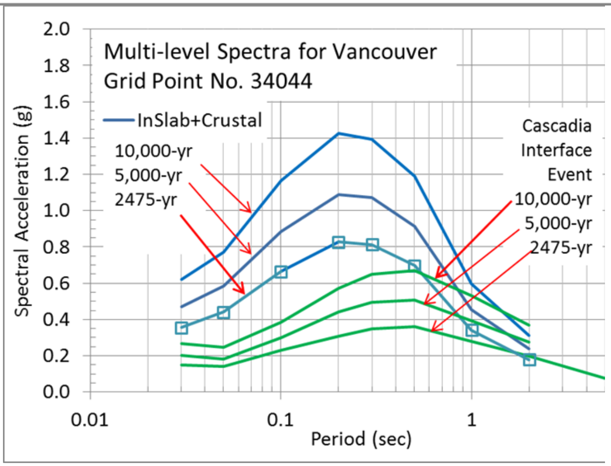
Seismic Slope Displacements for a Probability of 2%/50 years

Legend:
Red - ALL Source
Green - Interface
Blue – InSlab/Crustal

Vancouver Grid Point
No. 34044 Ts=0.33 sec
At 28.21 cm,
P1 = 0.0002884
P2 = 0.0001095

*using VLOOKUP in Excel:
P = P1 + P2
~= 0.000400





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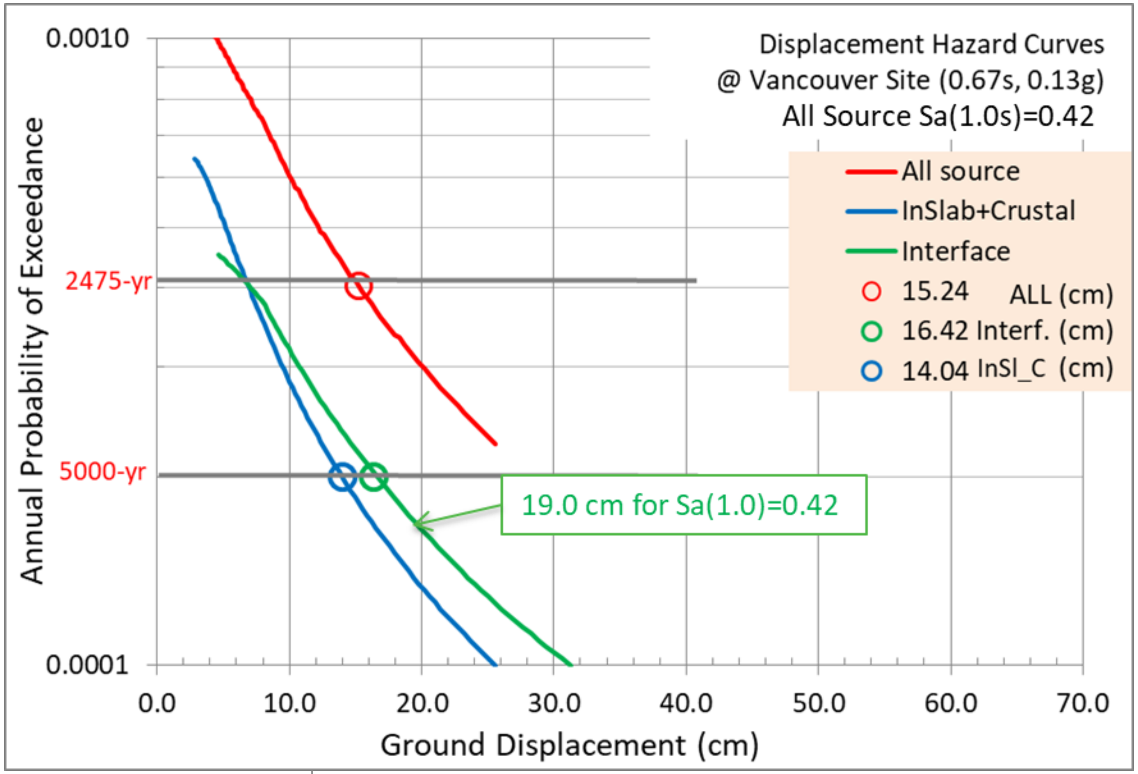
Seismic Slope Displacements for a Probability of 2%/50 years

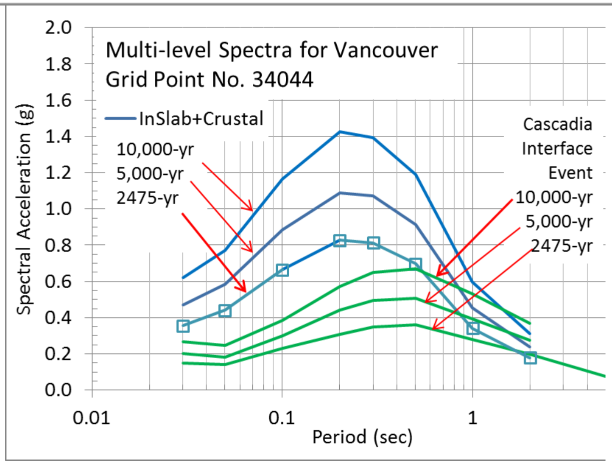
Legend:
Red - ALL Source
Green - Interface
Blue – InSlab/Crustal

Vancouver Grid Point No. 34044

Site Slope Period:

Ts=0.67 sec





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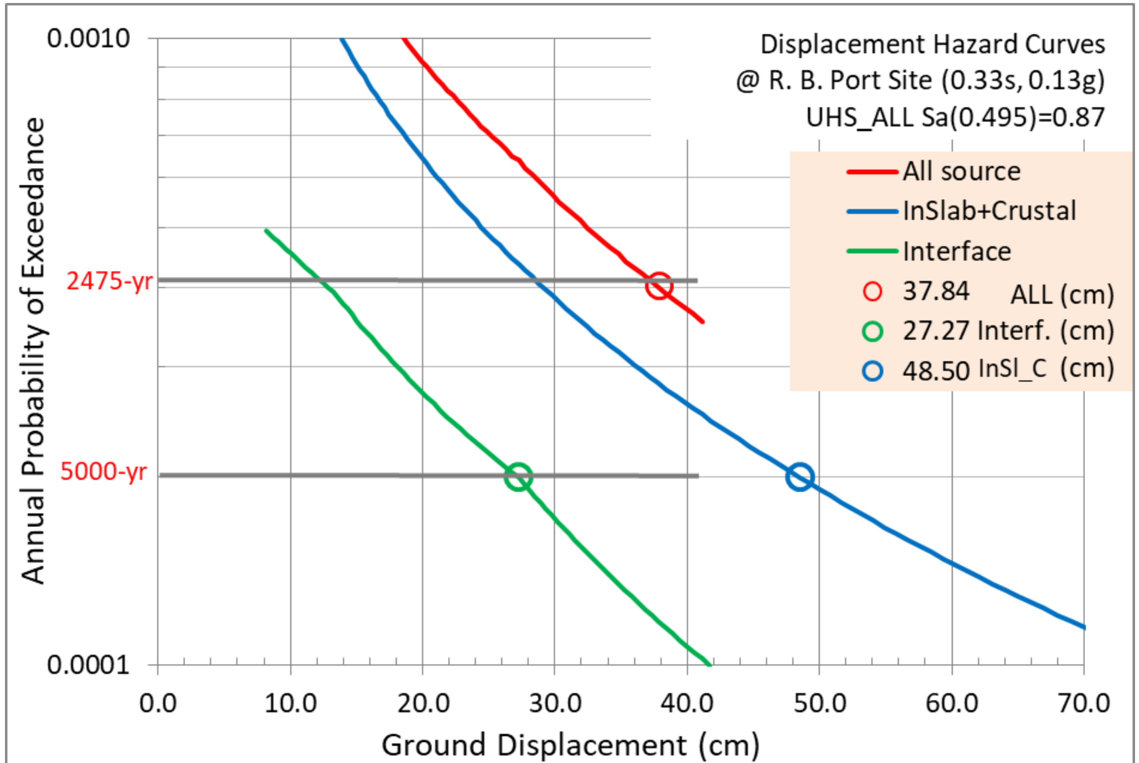
Seismic Slope Displacements for a Probability of 2%/50 years

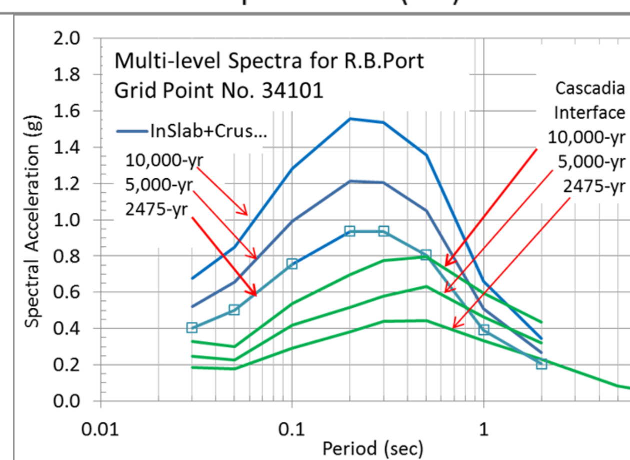
Legend:
Red - ALL Source
Green - Interface
Blue – InSlab/Crustal

Near the Roberts Bank Port at Grid Point No. 34101

Site Period

Ts=0.33 sec





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Seismic Slope Displacements for a Probability of 2%/50 years

	InSlab+Crustal Prob(D>d|D>0)			**P1**	*Interface Prob(D>d|D>0)*			**P2**	**P = P1 + P2 at D (cm)**	
Prob(D>d|D>0)	Sa(InSlab+	ln(D)	D (cm) ε=0	Prob(D>d)	Sa(Interface)	ln(D)	D (cm) ε=0	Prob(D>d)	Prob-TOTAL	No.
0.001000	0.2729	1.433	4.19	0.000816	0.1723	0.913	2.49	0.000544	0.001390	0
0.000977	0.2754	1.456	4.29	0.000806	0.1752	0.954	2.60	0.000551	0.001378	1
0.000955	0.2779	1.479	4.39	0.000795	0.1781	0.996	2.71	0.000557	0.001367	2
0.000933	0.2804	1.501	4.49	0.000784	0.1811	1.037	2.82	0.000562	0.001354	3
0.000631	0.3271	1.881	6.56	0.000592	0.2399	1.718	5.58	0.000544	0.001110	20
0.000617	0.3301	1.903	6.71	0.000581	0.2439	1.757	5.80	0.000538	0.001099	21
0.000603	0.3331	1.925	6.86	0.000570	0.2480	1.796	6.03	0.000532	0.001081	22
0.000447	0.3746	2.207	9.08	0.000437	0.3075	2.289	9.87	0.000431	0.000893	35
0.000437	0.3780	2.228	9.28	0.000428	0.3127	2.326	10.24	0.000423	0.000876	36
0.000427	0.3815	2.249	9.48	0.000419	0.3179	2.363	10.62	0.000415	0.000866	37
0.000417	0.3849	2.271	9.68	0.000410	0.3232	2.400	11.02	0.000407	0.000849	38
0.000407	0.3884	2.292	9.89	0.000401	0.3286	2.436	11.43	0.000398	0.000832	39
0.000398	0.3919	2.312	10.10	0.000392	0.3329	2.465	11.76	0.000390	0.000824	40
0.000245	0.4698	2.729	15.32	0.000245	0.4197	2.963	19.36	0.000245	0.000551	61
0.000240	0.4739	2.749	15.62	0.000239	0.4244	2.986	19.81	0.000239	0.000546	62
0.000234	0.4780	2.768	15.93	0.000234	0.4291	3.009	20.27	0.000234	0.000534	63
0.000229	0.4822	2.788	16.24	0.000229	0.4338	3.032	20.74	0.000229	0.000522	64
0.000224	0.4864	2.807	16.56	0.000223	0.4386	3.055	21.22	0.000223	0.000510	65
0.000219	0.4906	2.826	16.88	0.000218	0.4435	3.078	21.71	0.000218	0.000499	66
0.000214	0.4948	2.846	17.21	0.000214	0.4484	3.101	22.22	0.000213	0.000494	67
0.000209	0.4991	2.865	17.55	0.000209	0.4534	3.124	22.73	0.000209	0.000483	68
0.000204	0.5035	2.884	17.89	0.000204	0.4584	3.146	23.25	0.000204	0.000472	69
0.000200	0.5078	2.903	**18.23**	**0.000199**	0.4634	3.168	**23.77**	**0.000199**	0.000461	70
0.000195	0.5122	2.922	18.58	0.000195	0.4672	3.185	24.17	0.000195	0.000451	71
0.000191	0.5166	2.941	18.94	0.000190	0.4711	3.202	24.58	0.000190	0.000441	72
0.000186	0.5211	2.960	19.30	0.000186	0.4750	3.219	25.00	0.000186	0.000436	73
0.000182	0.5255	2.979	19.67	0.000182	0.4790	3.236	25.43	0.000182	0.000427	74
0.000178	0.5301	2.998	20.04	0.000178	0.4829	3.253	25.86	0.000178	0.000417	75
0.000174	0.5346	3.017	**20.42**	0.000174	0.4869	3.269	26.29	0.000174	**0.000408**	76

Legend:
Red - ALL Source
Green - Interface
Blue – InSlab/Crustal

Near the Roberts Bank Port at Grid Point No. 34101 Ts=0.67 sec
(1). P(D=0) ~ 45%
(2). At 20.42 cm,
P1=0.00174
P2=0.00234

*using VLOOKUP in Excel:
P = P1 + P2
~= 0.000408

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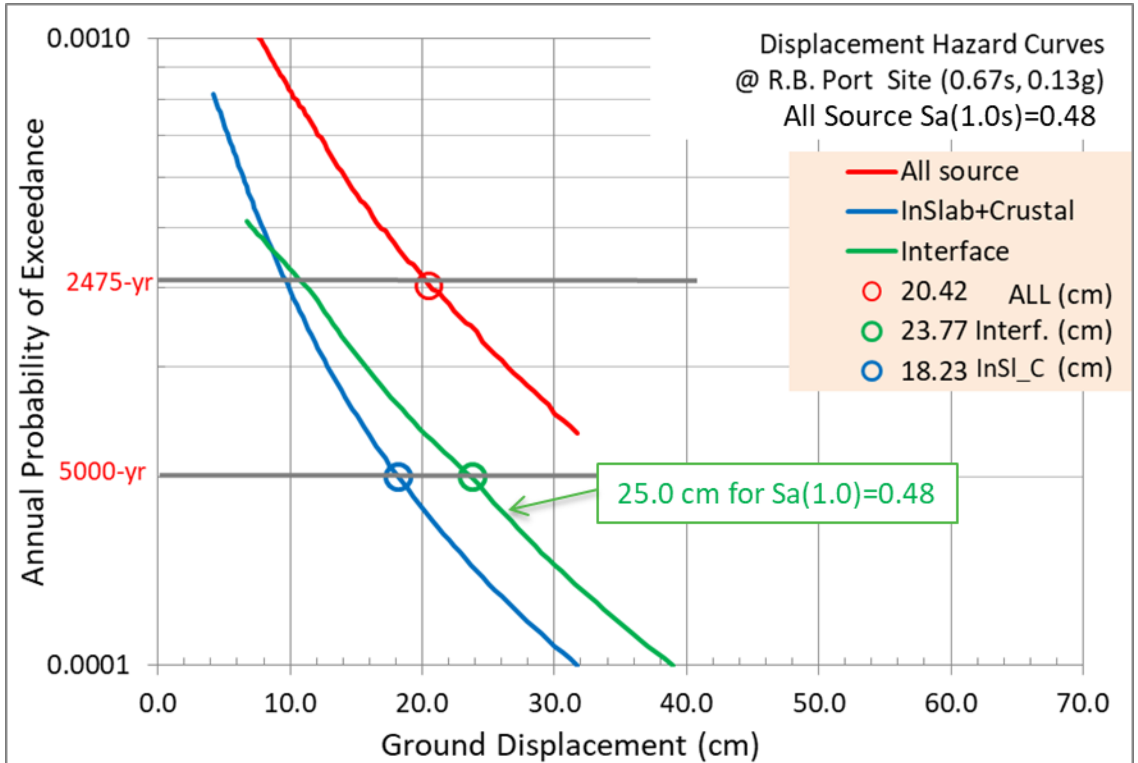
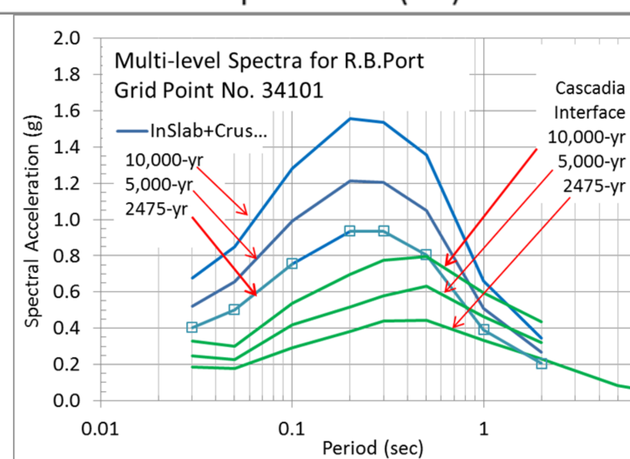
Seismic Slope Displacements for a Probability of 2%/50 years

Legend:
Red - ALL Source
Green - Interface
Blue – InSlab/Crustal

Near the Roberts Bank Port at Grid Point No. 34101 Ts=0.67 sec
At 20.42 cm,
P1=0.00174
P2=0.00234

*using VLOOKUP in Excel:
P = P1 + P2
~= 0.000408





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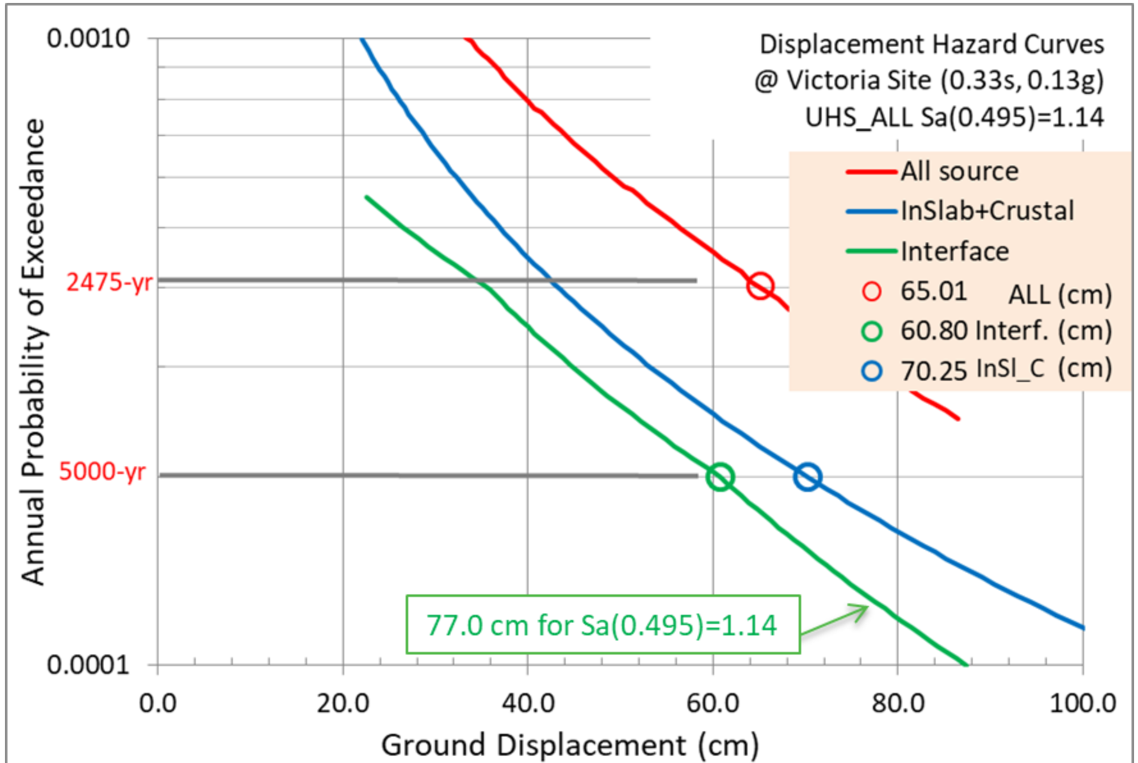
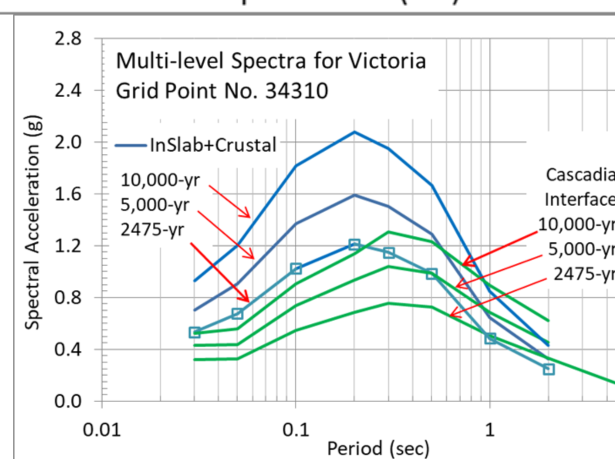
Seismic Slope Displacements for a Probability of 2%/50 years

Legend:
Red - ALL Source
Green - Interface
Blue – InSlab/Crustal

<u>Victoria Grid Point No. 34310 Ts=0.33 sec</u>
At 65.01 cm,
P1=0.00224
P2=0.00176

*using VLOOKUP in Excel:
P = P1 + P2
~= 0.000402





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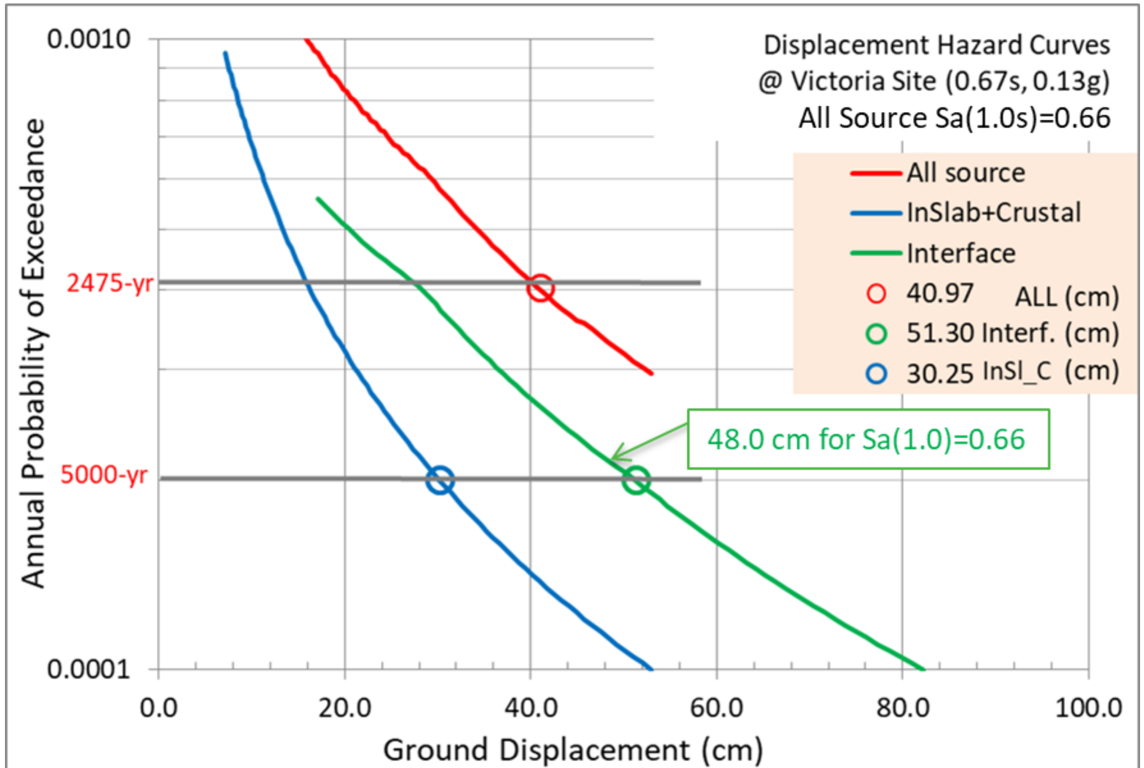
Seismic Slope Displacements for a Probability of 2%/50 years

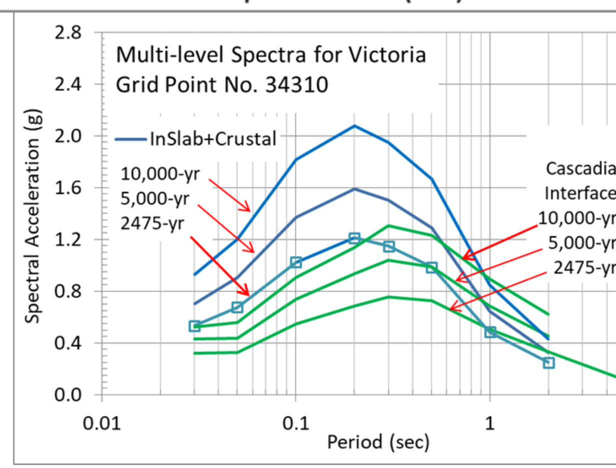
Legend:
Red - ALL Source
Green - Interface
Blue – InSlab/Crustal

Victoria Grid Point No. 34310

Site Slope Period

Ts=0.67 s





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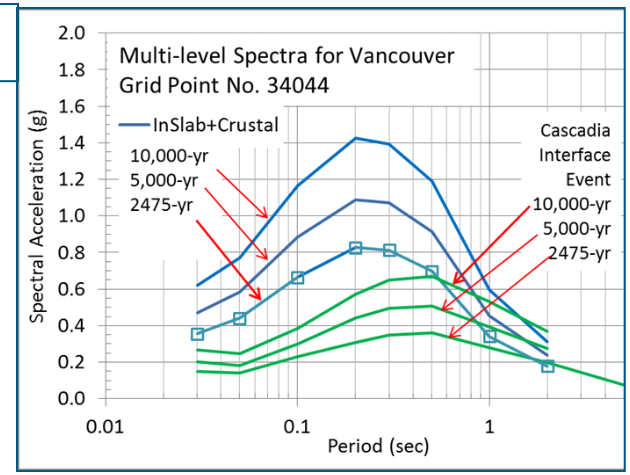
Seismic Slope Displacements for a Probability of 2%/50 years

- **Probability approach: Using Sa(1.5Ts) values from the individual spectra curves for the two earthquake sources: InSlab/Crustal and Subduction Interface**

YES

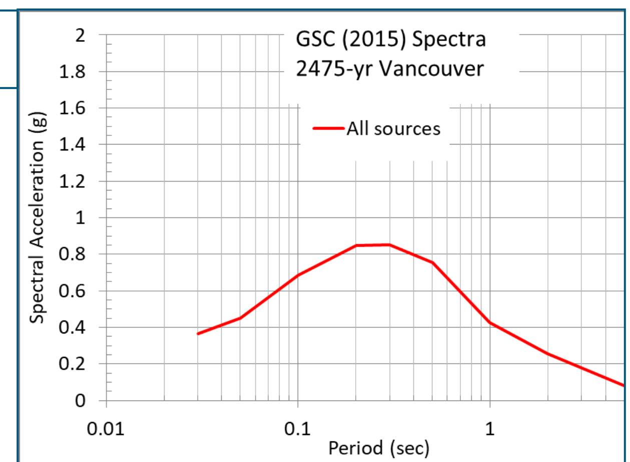


- In-adequate : Applying Sa values from the All-source spectra (UHS) for displacement calculation in equations for M~9 subduction :

Site Location	Site Period	slope sliding displacement (cm)		
		Probability Approach	2475-yr Sa for All-source	Error (%)
Vancouver at pt. 34044	0.33 s	28.21	(*)	(*)
	0.67 s	15.24	19	24.7
R.B.Port at pt. 34101	0.33 s	37.84	(*)	(*)
	0.67 s	20.42	25	22.4
Victoria at pt.34310	0.33 s	65.01	77	18.4
	0.67 s	40.97	48	17.2

(*) beyond subduction limit of 10,000-yr, likely out of equation bound

NO!



- The error in results could become larger when time history (TH) analyses are used for computing Factor of Safety (FoS) against liquefaction, as shown in Part 5, and in predicting displacements.

Seismic Slope Displacements for a Probability of 2%/50 years

- Relationships between displacements (D) from All-source and individual sources:
  - Half Probability Rule: D_2475-yr_All-source must exist between D_5000-yr_Interface and D_5000-yr_InSlab/Crustal; D_2475-yr_All-source must not be outside of D values of the two individual sources at Half of the Probability of the 2%/50-years, i.e., at the 1%/50 years or 5000-yr level.
  - Largest at the Same Probability Rule: D_2475-yr_All-source must be greater than each of the D_2475-yr_Interface and D_2475-yr_InSlab/Crustal; At the same probability level, D_2475-yr_All-source should be the largest among the three D values.
  - The D value from the less strong earthquake source in terms of response (displacement etc.), between the InSlab/Crustal and the Interface, would be determined up to the 10,000-yr level in order to determine the D_2475-yr_All-source. It is expected that extrapolation beyond the 10,000-yr level could be required in some limited cases, with likely small error in the D_2475-yr_All-source. Normally the D_2475-yr_All-source values can be determined within the 10,000-yr level as demonstrated in the displacement calculations using methods by Bray and Travasarou (2007) and Macedo et al. (2017).

Factors of Safety (FoS) against liquefaction for Probability of 2%/50 years for 1D Soil Column

- **Example location at Roberts Bank Port GSC Borehole FD95-S1 (150 m deep), near Grid Point No. 34101 (49.08 N; -123.264W). Shear wave velocity and soil stratigraphy at FD95-S1 were used.**

Crow, H.L, Good, R.L., Hunter, J.A., Burns, R.A., Reman, A., and Russell, H.A.J., 2015. **Borehole geophysical logs in unconsolidated sediments across Canada; Geological Survey of Canada, GSC Open File 7591**

Fraser Delta, BC: Quaternary sediments, up to several hundred metres thick, underlie much of the Fraser Lowland and Fraser Delta. This succession consists of sediment deposited during at least three glaciations and intervening interglaciations, and is made up of till and stratified sediment packages separated by unconformities (Clague et al., 1991; Clague, 1998). Interglacial paleosols and associated sediment occur locally.

Logging was conducted in 46 boreholes to determine the structure and geotechnical parameters of the delta and glacial stratigraphies in support of earthquake hazard studies in the region (e.g. Hunter et al., 1994; Hunter, 1995; Luternauer and Hunter, 1996; Hunter et al., 1998a,b). Boreholes intercept sediment consisting of alternating strata of mud and sand interpreted to be Holocene topset and foreset deposits of the Fraser River delta, and underlying Pleistocene sediment (Hunter et al., 1998a; Christian et al., 1998). The deepest well is the Richmond well (FD96-1) drilled by the GSC to a depth of 330 m (Dallimore et al., 1995, 1996). These data are further supported by logs in a 600 m deep borehole, the Conoco Dynamic Mud Bay well that penetrates to Miocene age sediment (not part of this data release). Most of the dataset consists of three logs (natural gamma, inductive conductivity and magnetic susceptibility) and P-wave and S-wave downhole measurements.

Factors of Safety (FoS) against liquefaction for Probability of 2%/50 years for 1D Soil Column

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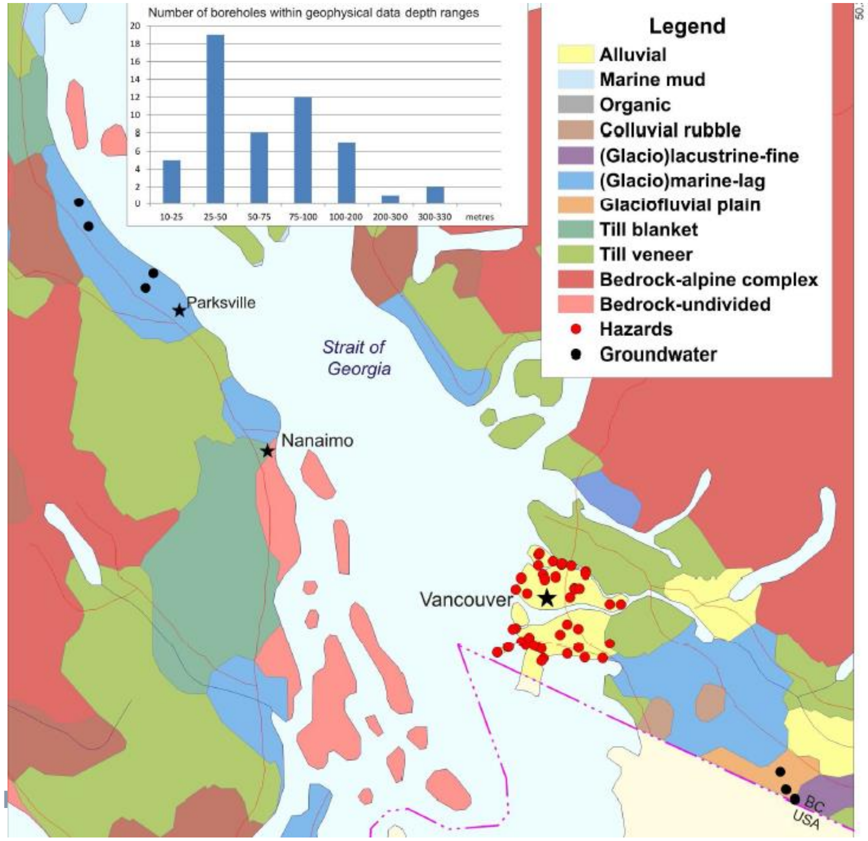
Figure 4 in Open File 7591 (2015): Boreholes on the BC mainland (Fraser delta and Abbotsford), and in the Nanaimo lowlands near Parksville on Vancouver Island. Surficial geology modified from Fulton (1995). Total of 54 boreholes in this region



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Factors of Safety (FoS) against liquefaction for Probability of 2%/50 years for 1D Soil Column

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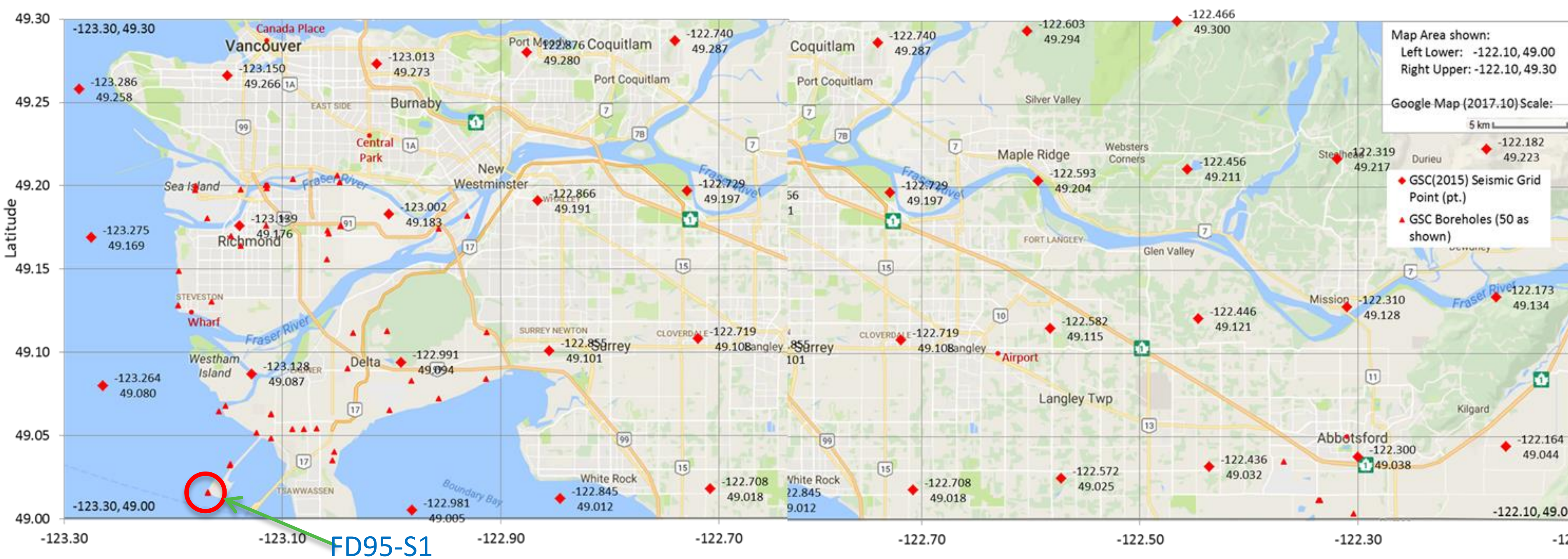
- **See below: Greater Vancouver Region for GSC(2015) Seismic Grid and Boreholes**



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Factors of Safety (FoS) against liquefaction for Probability of 2%/50 years for 1D Soil Column

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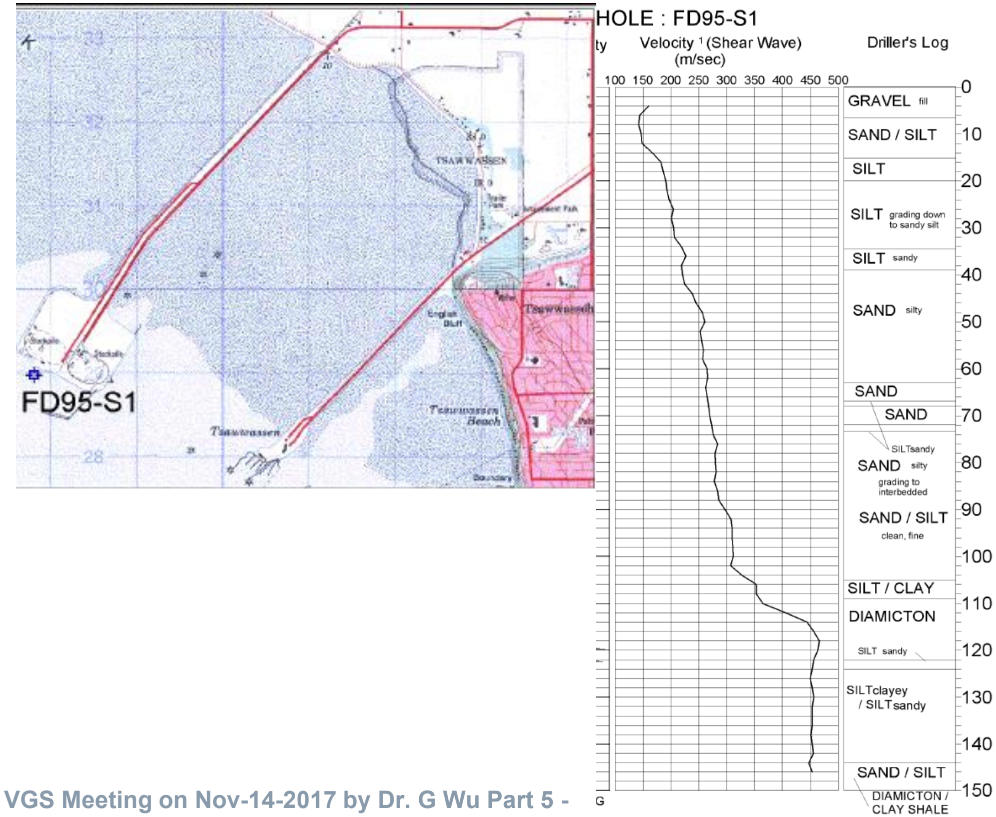

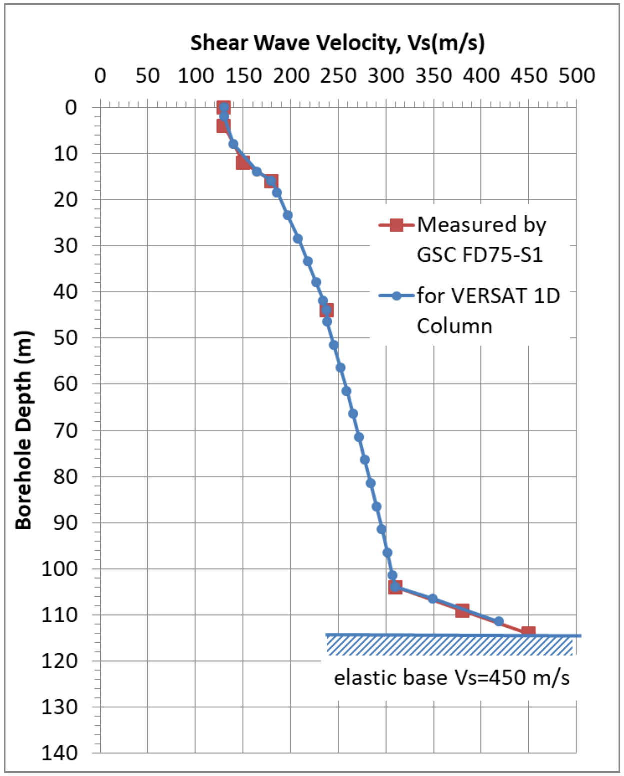

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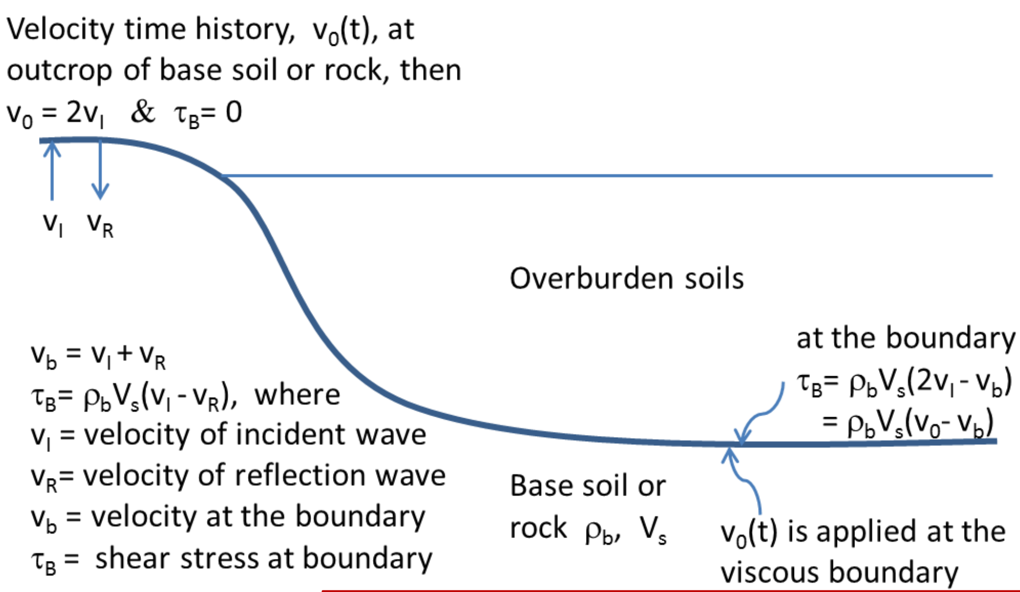
Factors of Safety (FoS) against liquefaction for Probability of 2%/50 years for 1D Soil Column

- **VERSAT-1D Soil Column with Elastic Base (or Compliance Base, or Viscous Base Boundary) by applying Outcropping Velocity Time History (TH) Input**
- **Figure 8 of VERSAT Technical Manual (Wutec Geotechnical Int. 2016): The elastic base model with a viscous boundary**

Surface outcropping motions on firm ground with Vs30 of 450 m/s: Applicable for GSC (2015) seismic hazard values



Within motions (114 m below ground surface) on firm ground with Vs30 of 450 m/s are different from the outcropping motions, likely lower.

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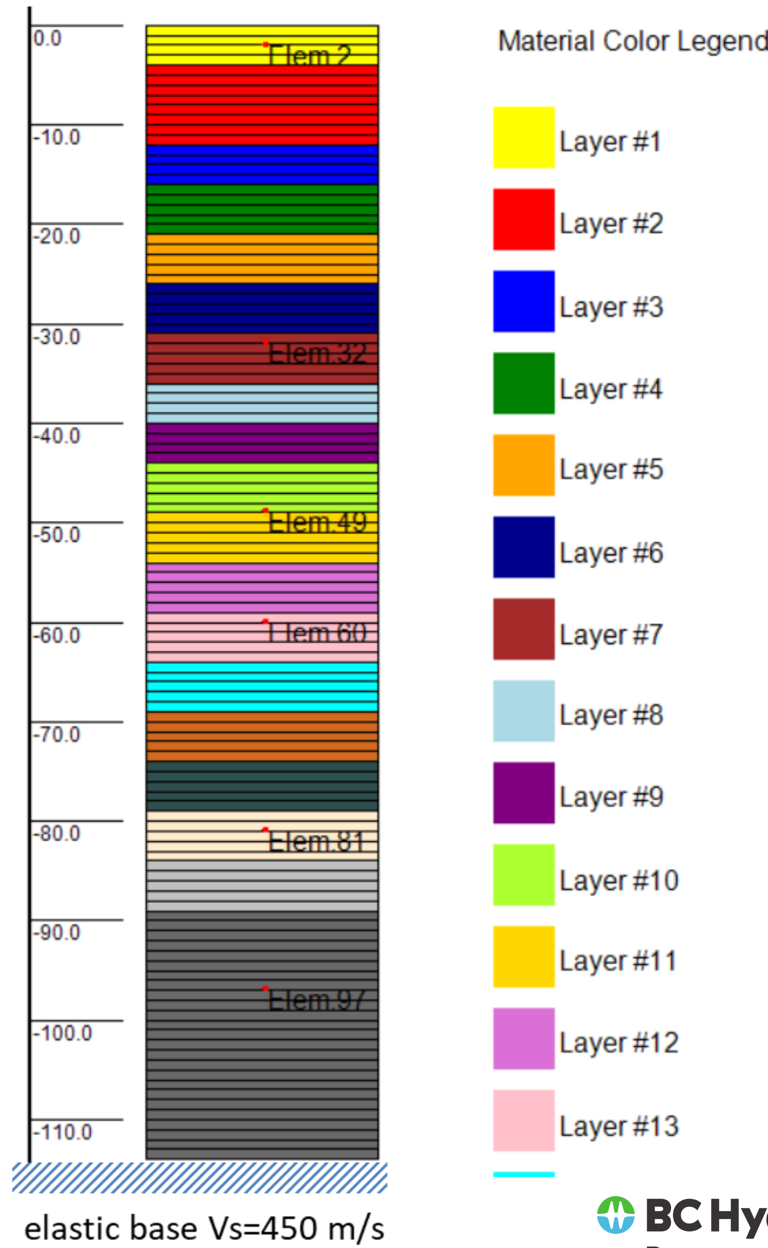
Factors of Safety (FoS) against liquefaction for Probability of 2%/50 years: VERSAT 1D Soil Model

- Using nonlinear finite element time history analyses (VERSAT-1D, Wutec 2016)
- VERSAT 1D Soil Model: 23 layers used in the model for a total of 114 soil elements (1 m thick each); elastic base with Vs=450 m/s; outcropping velocity TH applied to the model



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Factors of Safety (FoS) against liquefaction for Probability of 2%/50 years

- Using nonlinear finite element time history analyses (VERSAT-1D, Wutec 2016)
- VERSAT-1D Site Response Analysis: TOTAL STRESS METHOD
- Assuming (N1)60 = 24 for FoS against liquefaction

GSC FD95-S1 at Roberts Bank Port - Calculating Kg to matching Vs profile with the GSC data - VERSAT-1D dynamic runs					
	Pa = 101.3	m=n=0		Kb = 3*Kg for 1D Analysis	
Depth (m)	Unit Weight (kN/m^3)	VERSAT-Kg	G_max (kPa)	Vs (m/s)	Layer No.
0				130.2	
4	18.0	307	31099	130.2	1
12	19.0	375	37988	140.0	2
16	19.0	521	52777	165.1	3
16	19.0	620	62806	180.1	
21	19.0	661	66995	186.0	4
26	19.0	744	75372	197.3	5
31	19.0	827	83750	207.9	6
36	19.0	909	92127	218.1	7
40	19.0	984	99667	226.8	8
44	19.0	1050	106369	234.4	9
44	19.0	1083	109708	238.0	
49	19.5	1116	113096	238.5	10
54	19.5	1183	119873	245.6	11
59	19.5	1250	126650	252.4	12
64	19.5	1317	133427	259.1	13
69	19.5	1384	140204	265.6	14
74	19.5	1451	146981	271.9	15
79	19.5	1518	153758	278.1	16
84	19.5	1585	160535	284.2	17
89	19.5	1652	167312	290.1	18
94	19.5	1719	174089	295.9	19
99	19.5	1785	180866	301.6	20
104	19.5	1852	187643	307.2	21
104	19.5	1886	191052	310.0	
109	19.6	2415	244589	349.7	22
114	19.6	3472	351663	419.3	23
114	**19.6**	**4000**	**405200**	**450.1**	

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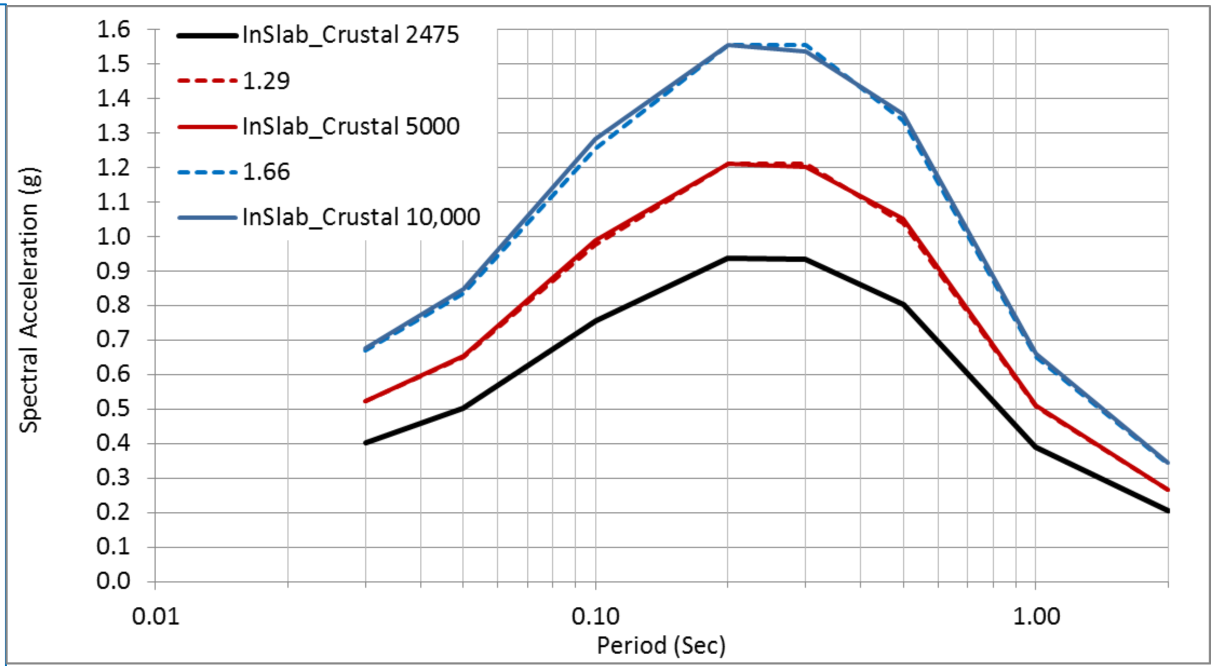
Factors of Safety (FoS) against liquefaction for Probability of 2%/50 years

- @R.B.Port pt.34101
- InSlab/Crustal Source

- Using nonlinear finite element time history analyses (VERSAT-1D, Wutec 2016)
- TH Selections: 6 THs for InSlab and 6 THs for Crustal
- Scaling factor 1.29 from 2475-yr to 5000-yr; and 1.66 to 10,000-yr



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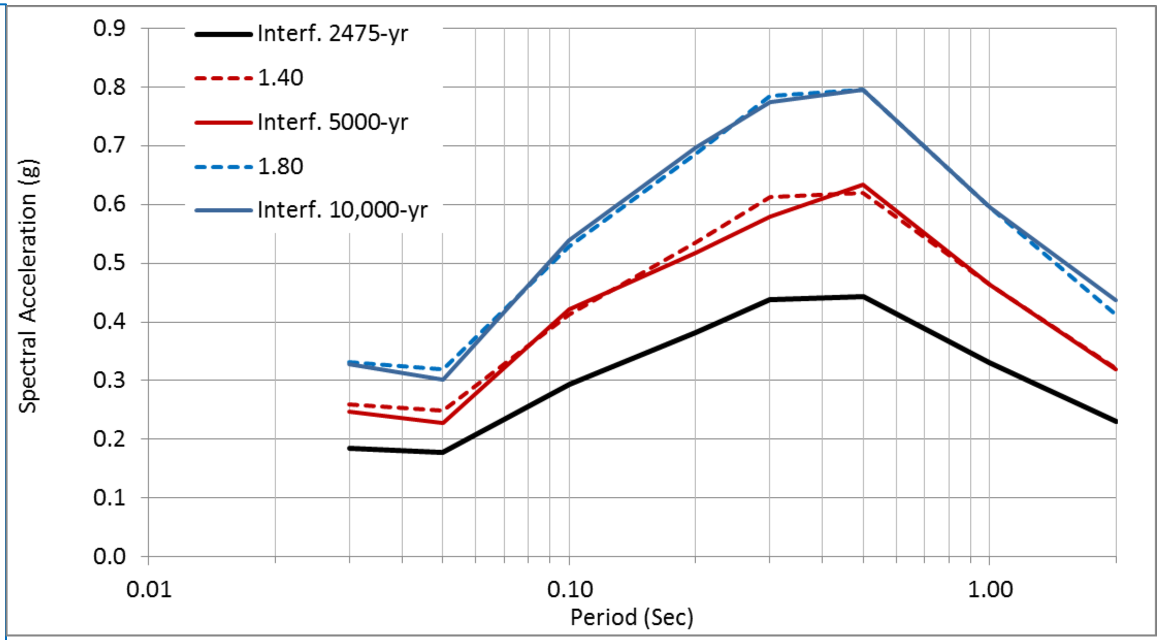
Factors of Safety (FoS) against liquefaction for Probability of 2%/50 years

- @R.B.Port pt.34101
- Subduction Interface

- Using nonlinear finite element time history analyses (VERSAT-1D, Wutec 2016)
- TH Selections: 11 THs for Subduction Interface
- Scaling factor 1.40 from 2475-yr level to 5000-yr, and 1.60 used for 7500-yr



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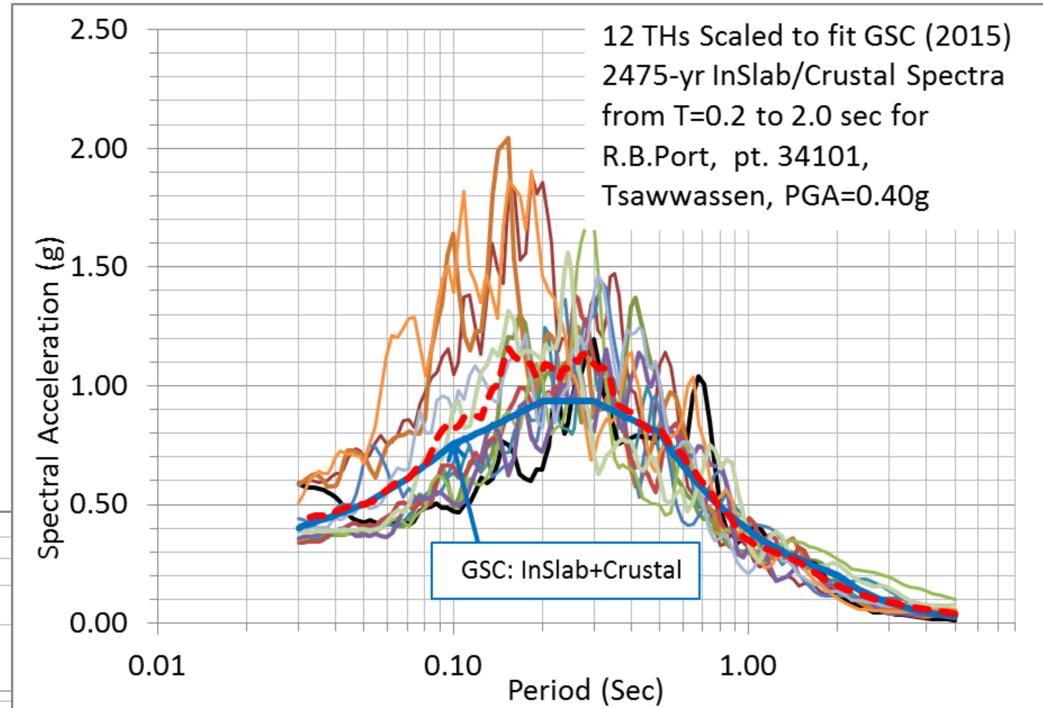
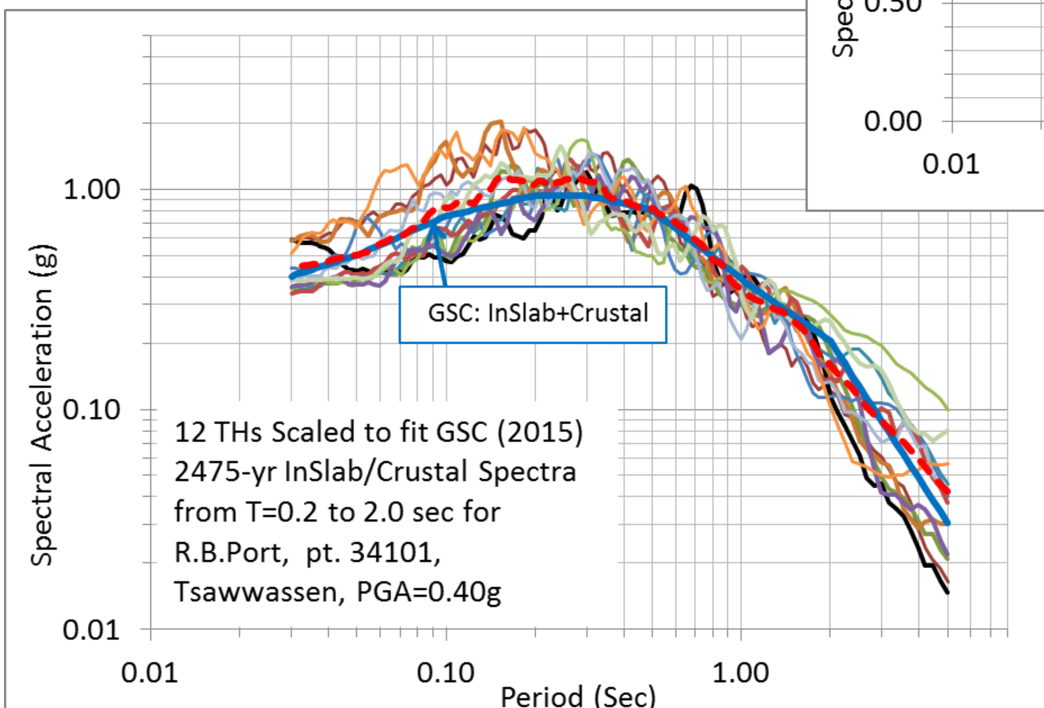
Factors of Safety (FoS) against liquefaction for Probability of 2%/50 years:

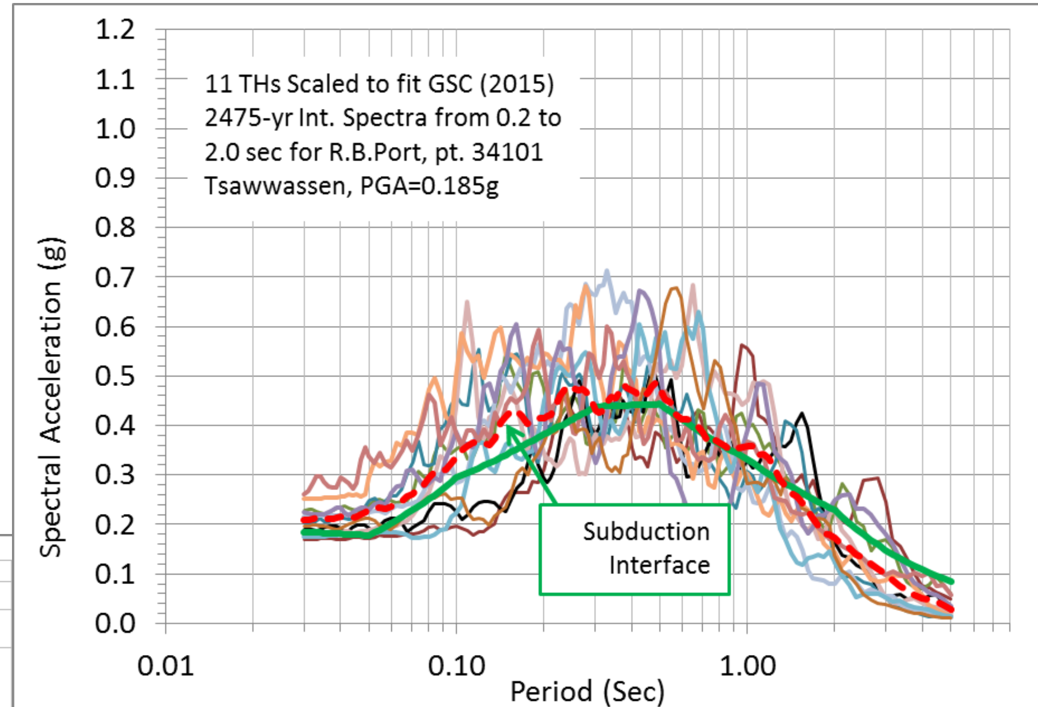


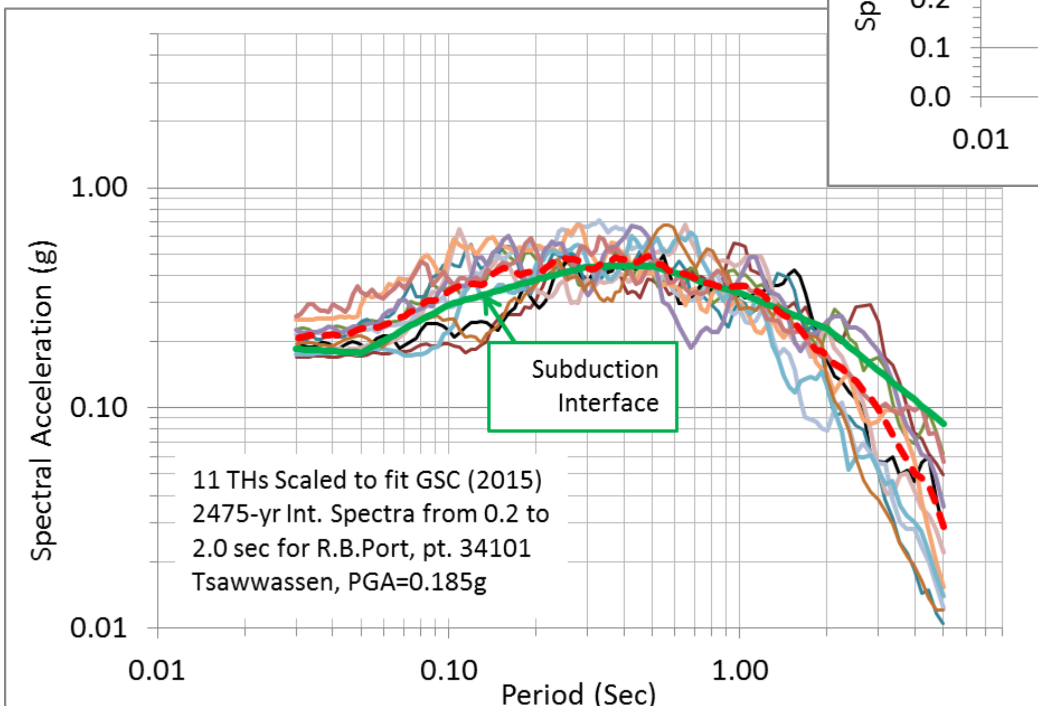


12 InSlab/Crustal Ground Motions (GM) for 2475-yr:

PGA =0.40g

Factors of Safety (FoS) against liquefaction for Probability of 2%/50 years:





11 Subduction Interface

GM for 2475-yr

PGA = 0.20g

Factors of Safety (FoS) against liquefaction for Probability of 2%/50 years:

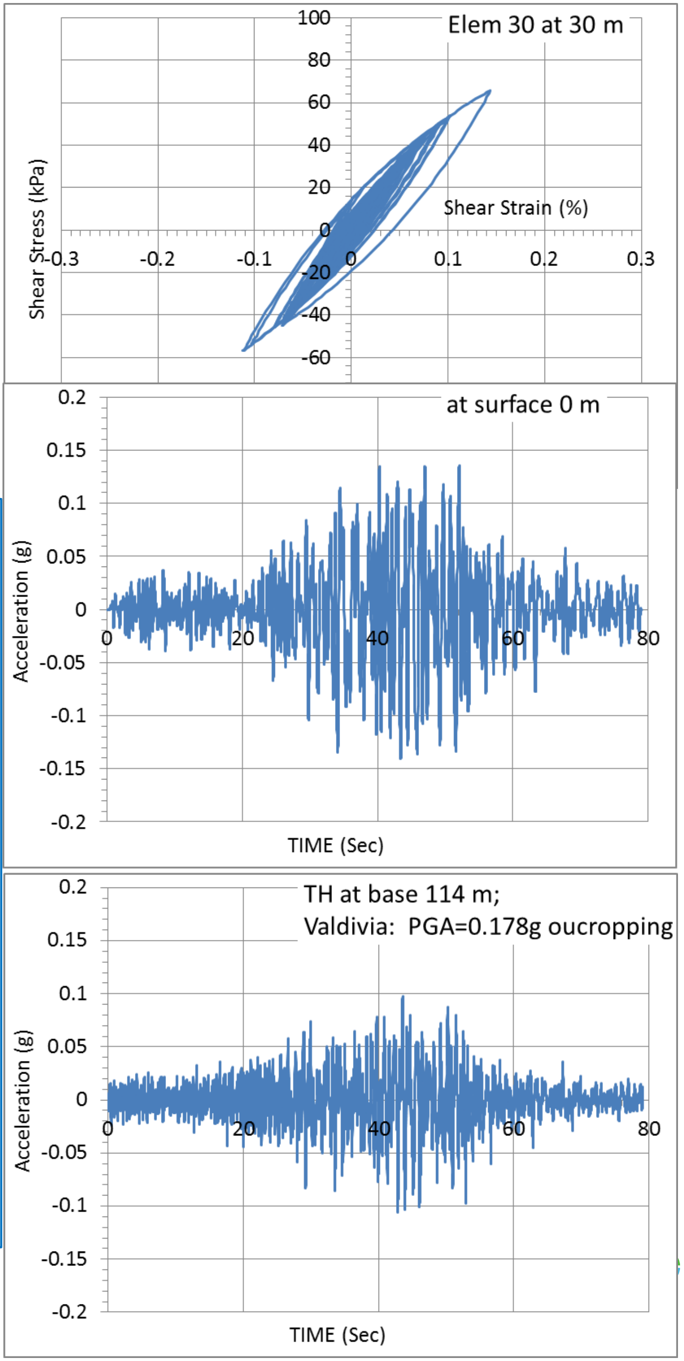
12 InSlab/Crustal and 11 Subduction Interface Ground Motions (GM) linearly scaled to 2475-yr level for VERSAT 1D Site Response Analysis

Ground Motions Linearly Scaled for GSC (2015) 2475-yr InSlab/Crustal and Subduction Interface Spectra for for R.B. Port, i.e., pt. 34101

Set	Earthquake Name	Date	Magnitude	Recording Station	Duration (sec)	PGA [g]	PGV [m/s]	PGD [m]	Arias Int. [m/s]	5%-95% [sec]
Subduction Interface Ground Motions						0.201				
1	Japan Tohoku	11-Mar-2011	9.0	FKS020	210.0	**0.168**	0.307	0.135	2.3	112.7
2	Japan Tohoku	11-Mar-2011	9.0	IWTH18	210.0	**0.247**	0.375	0.218	2.2	85.8
3	Japan Tohoku	11-Mar-2011	9.0	IWTH26	210.0	**0.212**	0.289	0.18	2.3	100.0
4	Chile Maule	27-Feb-2010	8.8	Santiago La Florida	208.0	**0.247**	0.208	0.068	1.9	39.8
5	Chile Maule	27-Feb-2010	8.8	Matanzas	120.4	**0.173**	0.177	0.052	1.6	34.7
6	Japan Tohoku	11-Mar-2011	9.0	MYG006	210.0	**0.184**	0.236	0.094	1.7	110.2
7	Japan Tohoku	11-Mar-2011	9.0	MYG010	210.0	**0.19**	0.195	0.043	2.2	105.1
8	Japan Tohoku	11-Mar-2011	9.0	MYG017	210.0	**0.189**	0.209	0.043	2.1	105.2
9	Japan Tohoku	11-Mar-2011	9.0	MYGH06	210.0	**0.214**	0.337	0.115	1.5	88.2
10	Chile Maule	27-Feb-2010	8.8	Santiago Penalolen	171.0	**0.214**	0.172	0.048	1.9	35.0
11	Chile Maule	27-Feb-2010	8.8	Valdivia	79.0	**0.178**	0.231	0.467	1.9	41.0
Crustal Ground Motions						0.376				
1	Northridge, CA	17-Jan-1994	6.7	Chalon Rd	31.1	**0.354**	0.312	0.061	1.7	9.0
2	Turkey, Kocaeli	17-Aug-1999	7.5	Izmit	30.0	**0.344**	0.572	0.363	1.8	13.3
3	Loma Prieta, CA	18-Oct-1989	6.9	Santa Teresa Hills	50.0	**0.482**	0.493	0.405	4.0	10.1
4	Iran, Tabas	16-Sep-1978	7.4	Tabas	33.0	**0.386**	0.446	0.169	2.4	16.5
6	Imperial Valley, CA	15-Oct-1979	6.5	Cerro Prieto CPE	63.8	**0.364**	0.25	0.113	5.7	30.0
5	Taiwan, Chi-Chi	20-Sep-1999	7.6	TCU071	50.4	**0.325**	0.278	0.090	3.4	24.0
InSlab Ground Motions						0.428				
1	Washington Nisqually	28-Feb-2001	6.8	Gig Harbour, Fire Station	99.0	**0.348**	0.322	0.136	2.4	24.6
2	Japan MiyagiOki	16-Aug-2005	7.2	MYG014	130.0	**0.575**	0.415	0.049	5.7	22.8
3	Western Washington	13-Apr-1949	6.9	Olympia Highway Lab	75.3	**0.355**	0.385	0.137	3.1	19.7
4	Washington Puget Sound	29-Apr-1965	6.7	Olympia Highway Lab	69.4	**0.534**	0.319	0.098	3.0	20.8
5	Washington, Nisqually	28-Feb-2001	6.8	Olympia Highway Lab	110.0	**0.355**	0.296	0.062	1.9	18.3
6	Mexico, Michoacan	11-Jan-1997	7.1	Villita, Stn VIL	55.1	**0.398**	0.444	0.124	1.7	15.9

Factors of Safety (FoS) against liquefaction for Probability of 2%/50 years: VERSAT 1D Soil Model

- Using nonlinear finite element time history analyses (VERSAT-1D, Wutec 2016)
- See TH response (2475-yr, Sub. Interface)
  - Nonlinear hysteretic Shear strain – stress curve for Elem 30 at 30 m depth
  - Accelerations at base (within) PGA 0.11g
  - Accelerations at ground surface PGA 0.14g; Note: Valdivia has PGA 0.178g at firm ground (Vs30 of 450 m/s) outcropping.



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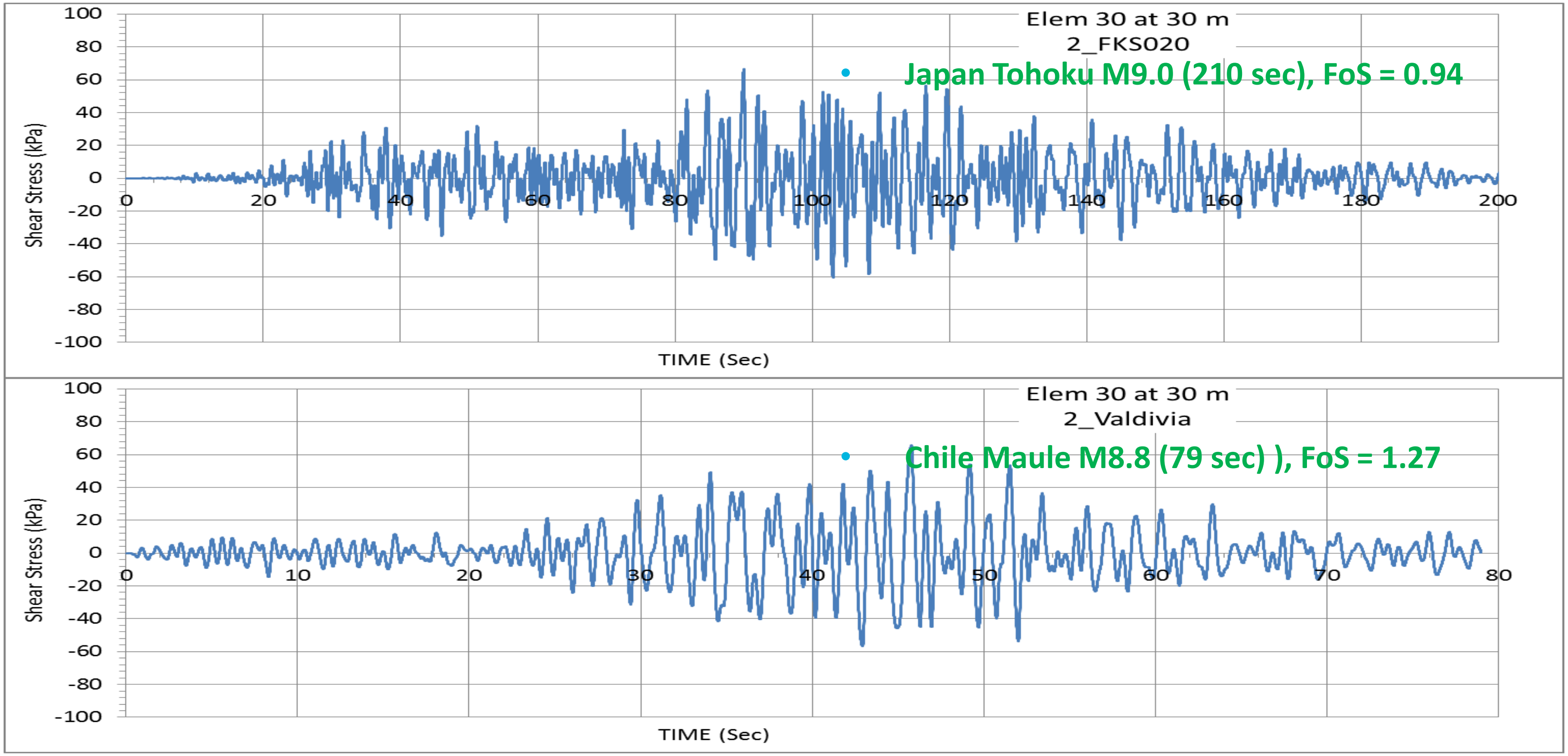
Factors of Safety (FoS) against liquefaction for Probability of 2%/50 years:

VERSAT 1D Factor of safety against liquefaction

- Cyclic Shear Stress Model for Liquefaction
    - **Shear stress THs for Elem 30 at 30 m depth (2475-yr, Subduction Interface), assuming (N1)60=24**



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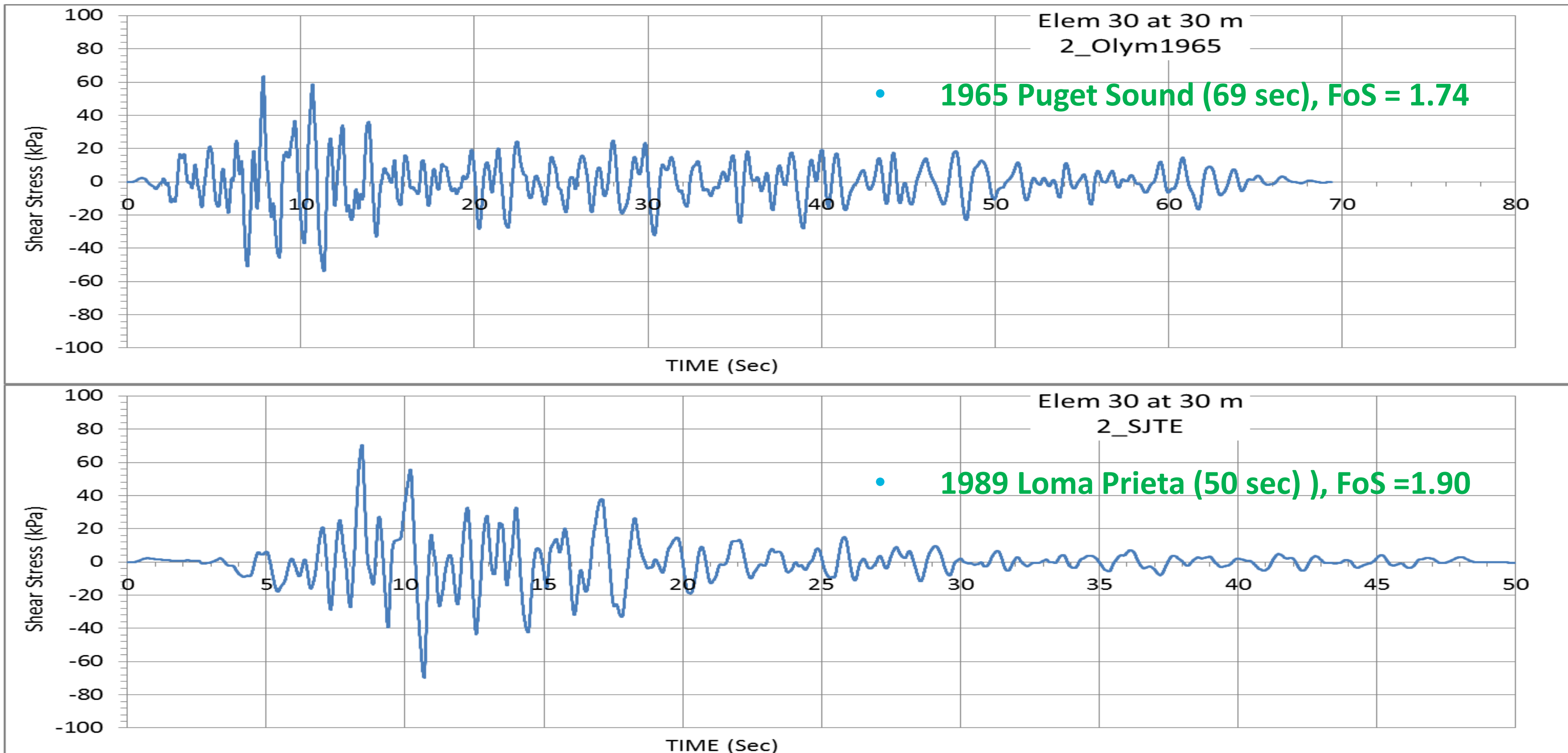
Factors of Safety (FoS) against liquefaction for Probability of 2%/50 years: VERSAT 1D Soil Model

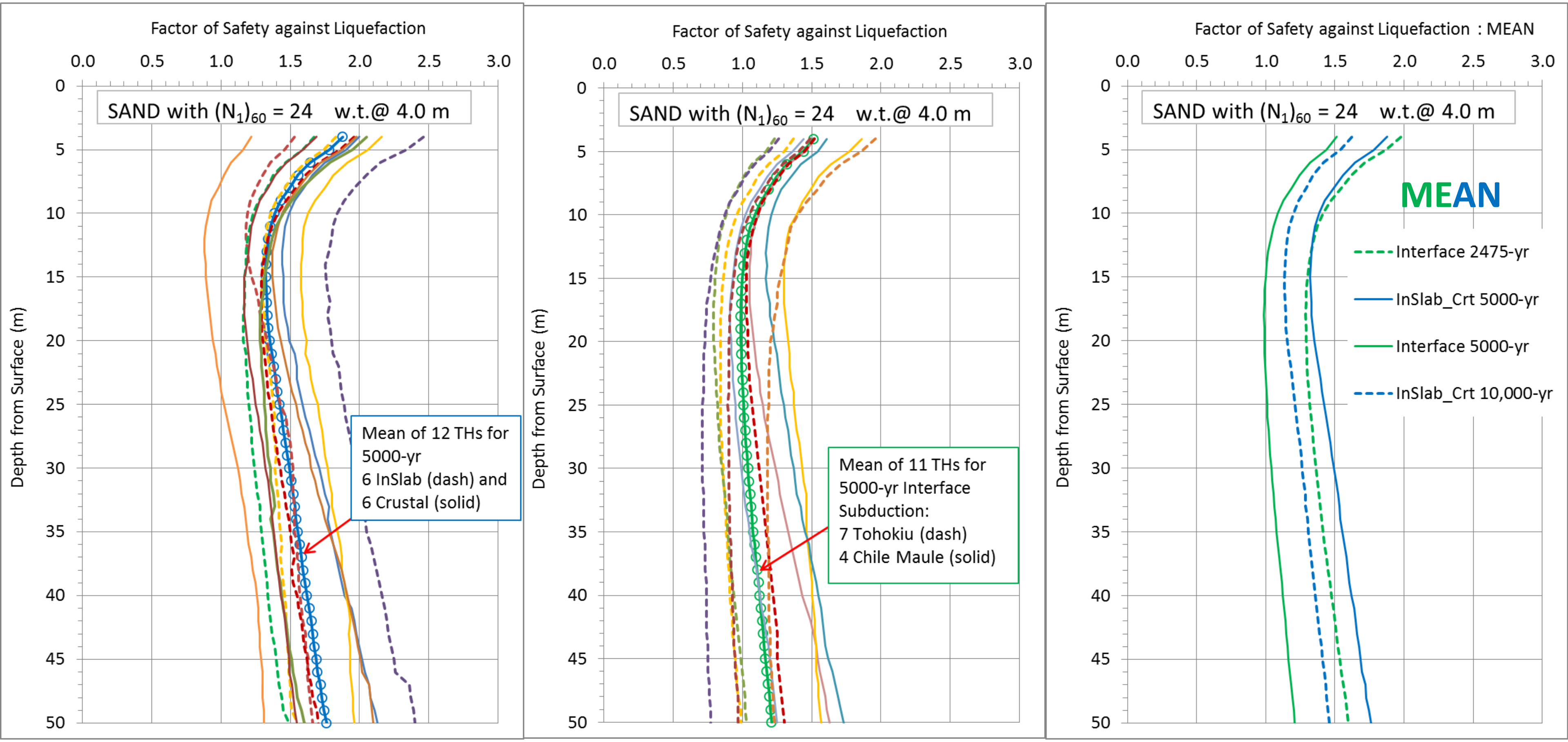
VERSAT 1D Factor of safety against liquefaction

- Cyclic Shear Stress Model for Liquefaction
- **Shear stress THs for Elem 30 at 30 m depth (2475-yr, InSlab/Crustal), assuming (N1)60=24**



Factors of Safety (FoS) against liquefaction for Probability of 2%/50 years: Method A – "use Mean"

Summary FoS for: 12 InSlab/Crustal and 11 Subduction Interface Time Histories (THs)



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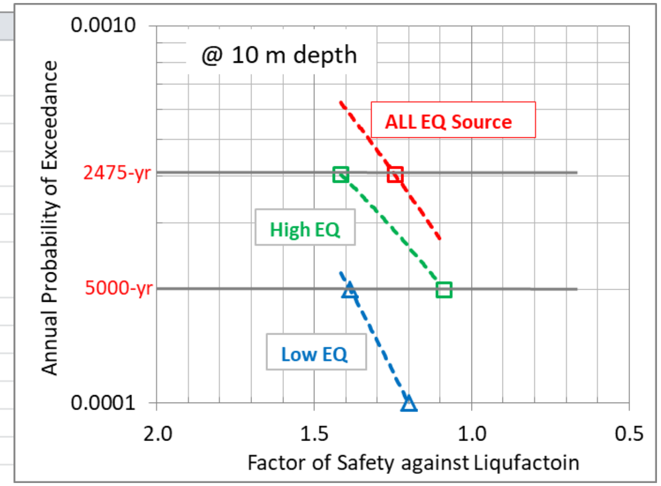
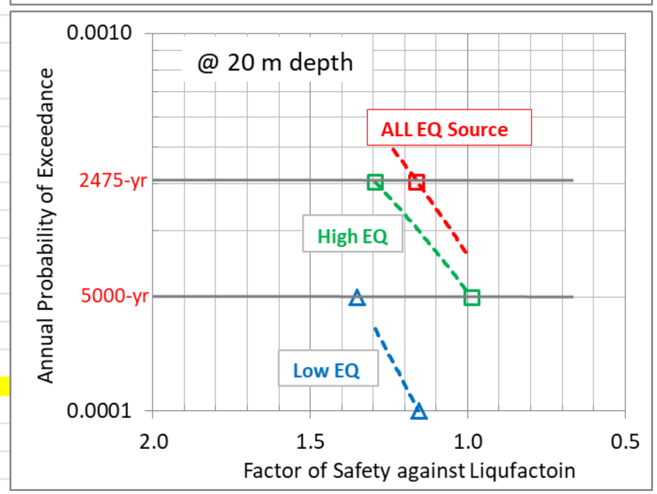
Factors of Safety (FoS) against liquefaction for Probability of 2%/50 years:

Determining FoS_All-Source from FoS_InSlab/Crustal and FoS_Interface, one by one, using Excel:

	A	B	C	D	E	F	I	J	K	L	M	N
1	Elem.	High EQ 2475-yr & 5000-yr		Low EQ 5000-yr and 10,000-yr		Combined Hazard		High of two EQs: Interf. or (InSl+Crt)		Lower of the two EQs, or Low EQ		Combined Hazard
2	No	0.0004	0.0002	0.0002	0.0001	0.0004		2475-yr	5000-yr	5000-yr	10000-yr	2475-yr
3	1	2.049	1.550	1.876	1.613		X of 4-points	1.416	1.089	1.387	1.199	1.25
4	2	1.961	1.505	1.848	1.598		Slope	2.68		4.84		
5	3	1.963	1.507	1.859	1.606	above						
6	4	1.975	1.515	1.877	1.623	W.T.		Probabilities				
7	5	1.872	1.439	1.783	1.539	1.62	No.	High EQ Line	on Low EQ	=P1 + P2	Prob. For Vlookup	X-values
8	6	1.718	1.322	1.644	1.418		0	0.000404	0.000222	0.000626	0.000374	1.4164
9	7	1.620	1.245	1.557	1.345		1	0.000401	0.000219	0.000620	0.000380	1.4126
10	8	1.545	1.186	1.493	1.291	1.35	2	0.000398	0.000216	0.000614	0.000386	1.4089
11	9	1.472	1.129	1.429	1.236		3	0.000396	0.000213	0.000609	0.000391	1.4052
12	10	1.416	1.089	1.387	1.199	1.25	4	0.000393	0.000211	0.000603	0.000397	1.4016
13	11	1.375	1.055	1.358	1.168		5	0.000390	0.000208	0.000598	0.000402	1.3979
14	12	1.350	1.034	1.342	1.154	1.19	6	0.000387	0.000205	0.000593	0.000407	1.3942
15	13	1.327	1.017	1.332	1.143		7	0.000385	0.000203	0.000587	0.000413	1.3906
16	14	1.312	1.007	1.324	1.138		8	0.000382	0.000200	0.000582	0.000418	1.3869
17	15	1.302	0.998	1.323	1.135	1.16	9	0.000379	0.000198	0.000577	0.000423	1.3833
18	16	1.295	0.993	1.327	1.137		10	0.000377	0.000195	0.000572	0.000428	1.3796
19	17	1.292	0.989	1.332	1.140	1.15	11	0.000374	0.000193	0.000567	0.000433	1.3760
20	18	1.289	0.986	1.333	1.144		12	0.000371	0.000190	0.000562	0.000438	1.3724
21	19	1.292	0.988	1.342	1.147		13	0.000369	0.000188	0.000557	0.000443	1.3688
22	20	1.295	0.989	1.352	1.155	1.16	14	0.000366	0.000185	0.000552	0.000448	1.3652
23	21	1.295	0.992	1.367	1.165		15	0.000364	0.000183	0.000547	0.000453	1.3616
24	22	1.299	0.995	1.382	1.179	1.17	16	0.000361	0.000181	0.000542	0.000458	1.3581
25	23	1.304	0.999	1.394	1.190		17	0.000358	0.000179	0.000537	0.000463	1.3545
26	24	1.314	1.005	1.405	1.201		18	0.000356	0.000176	0.000532	0.000468	1.3509
27	25	1.319	1.008	1.422	1.209	1.19	19	0.000353	0.000174	0.000528	0.000472	1.3474
56							....	....	....	....	....	....
57	54	1.644	1.246	1.820	1.493		48	0.000288	0.000120	0.000409	0.000591	1.2485
58	55	1.654	1.254	1.829	1.501		49	0.000286	0.000119	0.000405	0.000595	1.2453
59	56	1.667	1.263	1.835	1.508		50	0.000284	0.000117	0.000402	0.000598	1.2420
60	57	1.678	1.271	1.844	1.521		51	0.000282	0.000116	0.000398	0.000602	1.2387





Factors of Safety (FoS) against liquefaction for Probability of 2%/50 years:

Method A "use Mean"

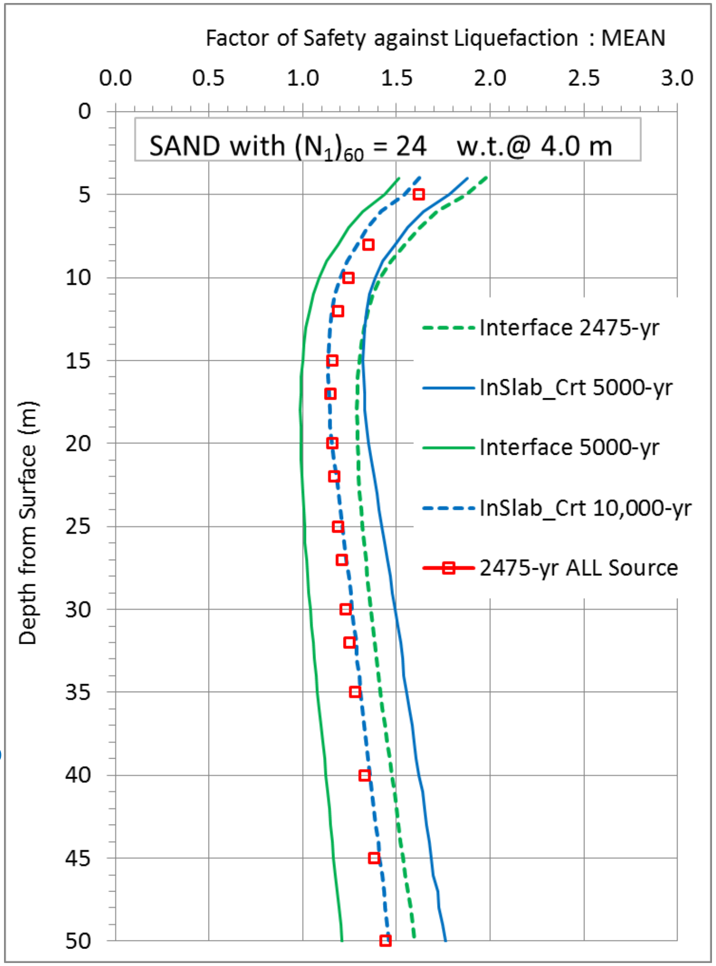
Pros:

- Requires least number of analyses to obtain performance results at one probability level, e.g., 2475-yr level (2%/50 years) or 10,000-yr;
- Straightforward and suitable for probability analysis involving 2 EQ sources, i.e., easy implementation

Cons:

- use "Mean" for aleatory uncertainties in results
  - Aleatory uncertainty (variability, stochastic uncertainty) characterizes the inherent randomness in the system under study - irreducible uncertainty such as material properties derived from lab testing; characterized by frequency distributions.
- Results between two probability levels require interpolation

Result: Method A "use Mean"



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Factors of Safety (FoS) against liquefaction for Probability of 2%/50 years:

Method B "all Cumulated"

Probability Method B Processing Data for FoS_Liq of R B Port at 10 m Depth 2017.11.04

Assumption: $(N_1)_{60}$ = 24					
InSlab+Crustal - max. 10,000-yr		Prob - Low	Prob - High	Δ -Probability	ΔP -each TH
EQ Level	Prob.	(X 10^{-3})			(12 THs)
1000-yr	0.001000	0.632			
2500-yr	0.000400	0.283	0.632	0.350	0.000029
5000-yr	0.000200	0.141	0.283	0.141	0.000012
10,000-yr	0.000100	0.045	0.141	0.097	0.000008
50000-yr	0.000020				
Interface Subduction - max. 7500-yr		Prob - Low	Prob - High	Δ -Probability	(11 THs)
EQ Level	Prob.	(X 10^{-3})			
1000-yr	0.001000	0.632			
2500-yr	0.000400	0.283	0.632	0.350	0.000032
5000-yr	0.000200	0.163	0.283	0.120	0.000011
7500-yr	0.000133	0.058	0.163	0.106	0.000010
40000-yr	0.000025				

	VERSAT output (*.SIG)	
	FoS_liq	Δ:Probability
InSlab/Crustal 2475-5000-10,000 -yr (12 Values from 12 THs for each AEF) _ Group 1	2.19	0.000029
	1.64	0.000029
	1.73	0.000029
	1.45	0.000029
	1.40	0.000029
	1.62	0.000029
	1.46	0.000029
	1.71	0.000029
	1.67	0.000029
	1.92	0.000029
	1.73	0.000029
	1.07	0.000029
	1.84	0.000012
	1.41	0.000012
	1.44	0.000012
	1.23	0.000012
	1.19	0.000012
	1.36	0.000012
	1.25	0.000012
	1.45	0.000012
	1.44	0.000012
	1.63	0.000012
	1.49	0.000012
	0.91	0.000012

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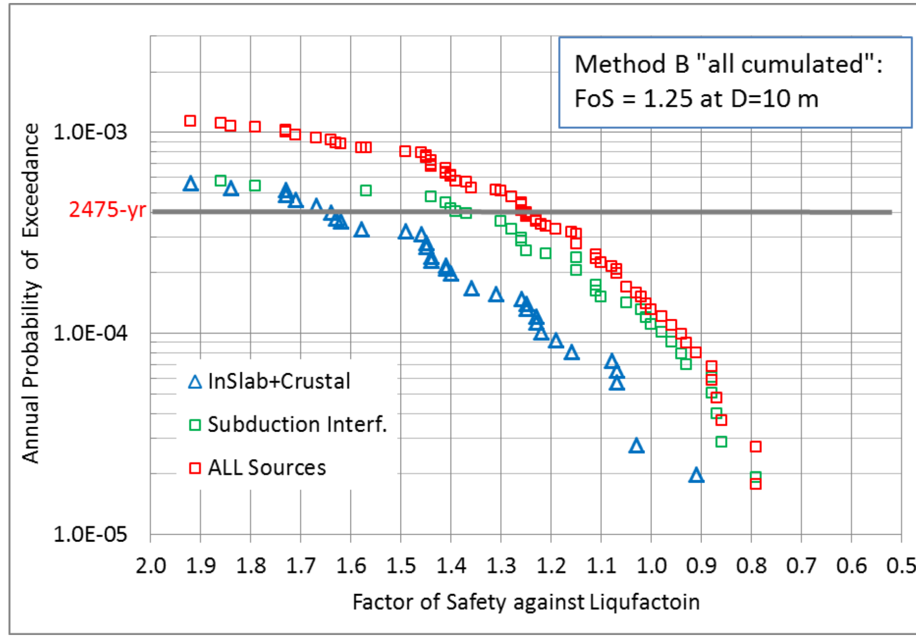
Factors of Safety (FoS) against liquefaction for Probability of 2%/50 years: Method B “all Cumulated”

Method B “all Cumulated”

0.91	0.000012	1.46
1.58	0.000008	1.49
1.23	0.000008	1.58
1.22	0.000008	1.62
1.07	0.000008	1.63
1.03	0.000008	1.64
1.16	0.000008	1.67
1.08	0.000008	1.71
1.25	0.000008	1.73
1.26	0.000008	1.73
1.41	0.000008	1.84
1.31	0.000008	1.92
0.79	0.000008	2.19
1.15	0.000032	0.79
1.44	0.000032	0.79
1.28	0.000032	0.86
1.79	0.000032	0.87
1.41	0.000032	0.88
1.26	0.000032	0.88
1.37	0.000032	0.93
1.15	0.000032	0.94
1.86	0.000032	0.96
1.57	0.000032	0.98
1.30	0.000032	1

Interface 2475-5000-7500 -yr (11 Values from 11 THs for each AEF) - Group 2

1.30	0.000032
0.87	0.000011
1.11	0.000011
0.98	0.000011
1.39	0.000011
1.11	0.000011
0.96	0.000011
1.05	0.000011
0.88	0.000011
1.40	0.000011
1.21	0.000011
1.02	0.000011
0.79	0.000010
1.00	0.000010
0.88	0.000010
1.25	0.000010
1.01	0.000010
0.86	0.000010
0.94	0.000010
0.79	0.000010
1.26	0.000010
1.10	0.000010
0.93	0.000010



	Method A "use Mean"	Method B "all cumulated"
Interface	1.42	1.4
InSlab/Crustal	1.63	1.64
All Sources	1.25	1.25

Factors of Safety (FoS) against liquefaction for Probability of 2%/50 years:

Method B "all Cumulated"

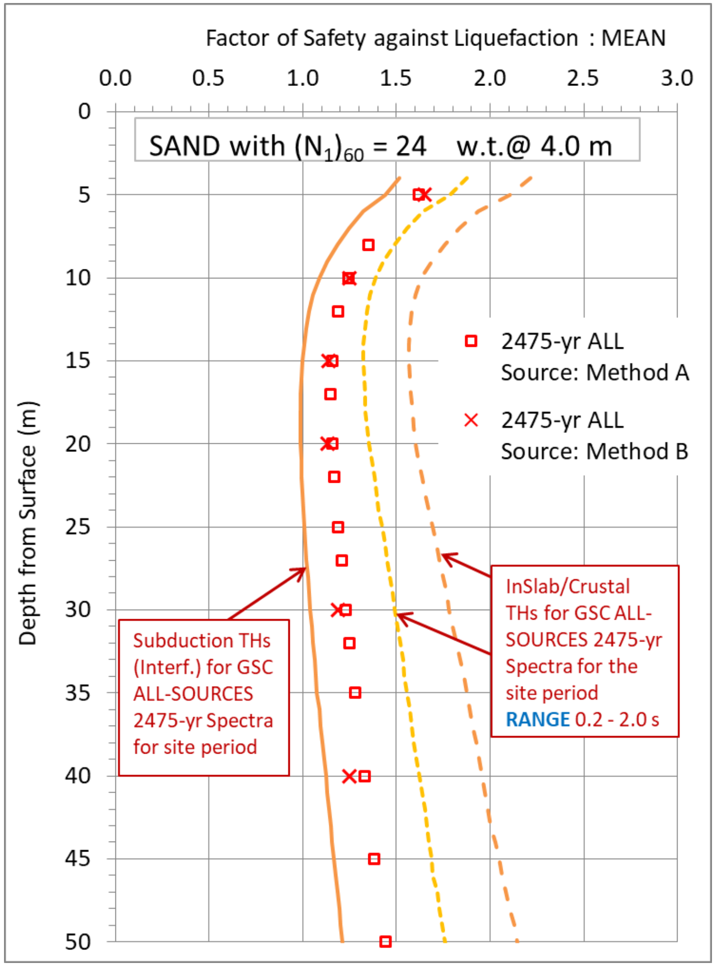
Pros:

- Aleatory uncertainties naturally included by using results from each of all analyses ;
- Suitable for analyses involving multiple EQ sources and in systematic risk analysis;
- Does not require interpolation of results between probability levels.

Cons:

- Require analyses to be completed at more than two probability levels;
- Require estimating incremental probability (ΔP), assumed Log-linear between two adjacent P.

Result: Method B "all Cumulated"



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Probability Approach for Ground and Structure Response to GSC 2015 Seismic Hazard including Crustal and Subduction Earthquake Sources

Conclusion Remarks (1)

1. Use of the Probability Approach will reduce the epistemic uncertainties when dealing with seismic hazard including both InSlab/Crustal (M~7) and Subduction (M~9) earthquake sources
   - Epistemic uncertainty (subjective uncertainty) characterizes the lack of knowledge, which is reducible uncertainty through increased understanding (research), or increased data, or through more relevant data. Characterized as degrees of "belief".
2. Don't be fooled by spectra (UHS) when M~7 and M~9 are mixed in contribution; spectral values are less impacting on ground and structural response (displacement, liquefaction) than earthquake magnitude; duration (5% – 95%) of a M~9 subduction quake could be 10 times longer than a M~7 crustal quake. Note: the energy released in a M~9 quake is about 100 times that in a M~7 quake.
3. Don't be fooled by seismologists – they have not yet incorporated the M~9 factor into their equations of solutions, ONLY spectra! We, engineers, are required to mange the M~9 factor.
4. Maintain traditional ways of solving engineering problems (such as using UHS, Site Class correction for hard rock) while cautiously moving into and applying new ideas (such as CMS for subduction quakes, kappa correction on spectra for hard rock); A new idea could represent direction for future solutions but it starts with a great uncertainty that requires data and research to reconcile to its maturity.

Conclusion Remarks (2)

5. The proposed Probability Approach for seismic hazard involving both M~7 and M~9 is a sensible method, not only accurate in theory but also practical in reality. In the example liquefaction analysis using VERSAT (Wutec Geot, 2016), 46 runs are conducted for the Probability Approach which are twice when the two sources (M~7 and M~9) are analyzed separately at one probability level (2%/50 years or 2475-yr level) for total of 23 runs (12 THs for InSlab/Crustal M~7 and 11 THs for Subduction M~9).
6. Use sensible method and apply engineers' priorities in engineering project works. We would not need 500 sets of THs for a probability analysis; instead 23 sets/46 runs as in the example base-case analysis.
7. Apply the "Half probability" Rule and the "Largest at the same probability" Rule when using the Probability Approach to plan the analyses for using either Method A or Method B.
8. Method A "use Mean" and Method B "all Cumulated" are both adequate approaches when only two EQ sources are of concern; and results from both methods are almost the same in the example.
9. Method B "all Cumulated" would be more suitable for analyses involving multiple EQ sources and in systematic risk analysis. It does not require interpolation of results between probability levels; and the aleatory uncertainties are inherently reflected in results.

Probability Approach for Ground and Structure Response to GSC 2015 Seismic Hazard including Crustal and Subduction Earthquake Sources

THE END

Questions ?