Reliability-based dynamic analyses for seismic design optimization in British Columbia

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BC Hydro & Wutec Geotechnical International

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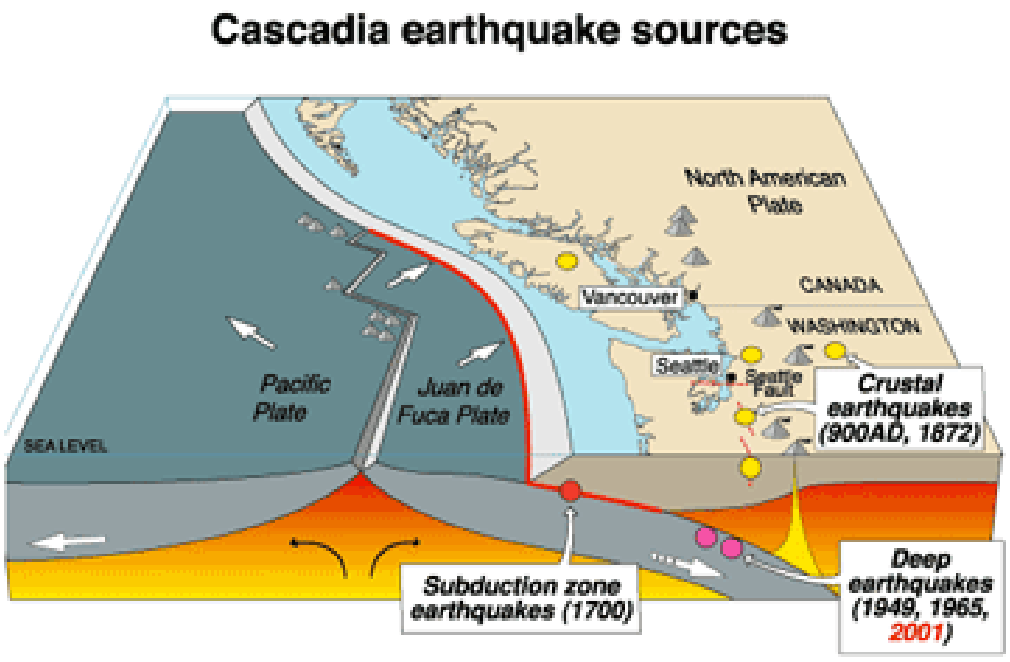
Earthquakes in Southwest BC:

Two earthquake sources with large difference in magnitude:

- M~9 for subduction Interface
- M~7 for Crustal and subduction Intra Slab (InSlab)



Outline

Reliability-based dynamic analyses for seismic design optimization in British Columbia

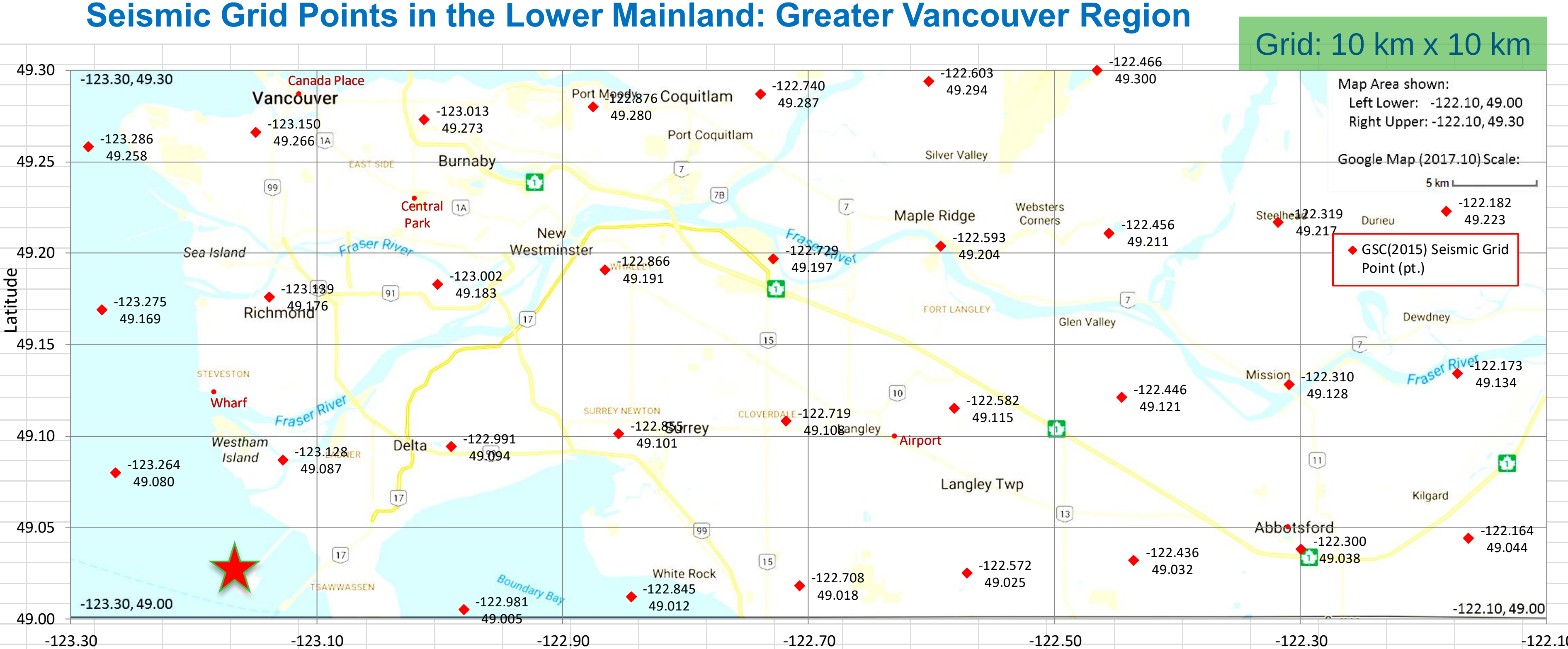
1. GSC (2015) 5th Generation Seismic Hazard Model for Probability Seismic Hazard Analysis (PSHA)
   - Seismic slope displacements from empirical equations for M9 and M7 earthquakes
2. Seismic Site Response and Liquefaction Analyses for a Soil Profile at Roberts Bank Port: PSPA Method
3. Reliability Based Soil Liquefaction Analyses Of the Soil Profile
4. Conclusion Remarks

Reference:

- Wu, G. 2017. Probability approach to GSC 2015 seismic hazard including crustal and subduction earthquake sources, VGS presentation in November 2017. http://v-g-s.ca/20172018-lecture-series
- Wu G. 2018 Probabilistic Approach to Design of Seismic Upgrade to Withstand both Crustal and Subduction Earthquake Sources, 2018 VGS Symposium http://v-g-s.ca/2018-proceedings

GSC (2015) fifth generation seismic hazard model: (Open File 8090 with 13148 pts)

Seismic Grid Points in the Lower Mainland: Greater Vancouver Region



Roberts Bank Port, GSC Borehole FD95-S1 (150 m deep)

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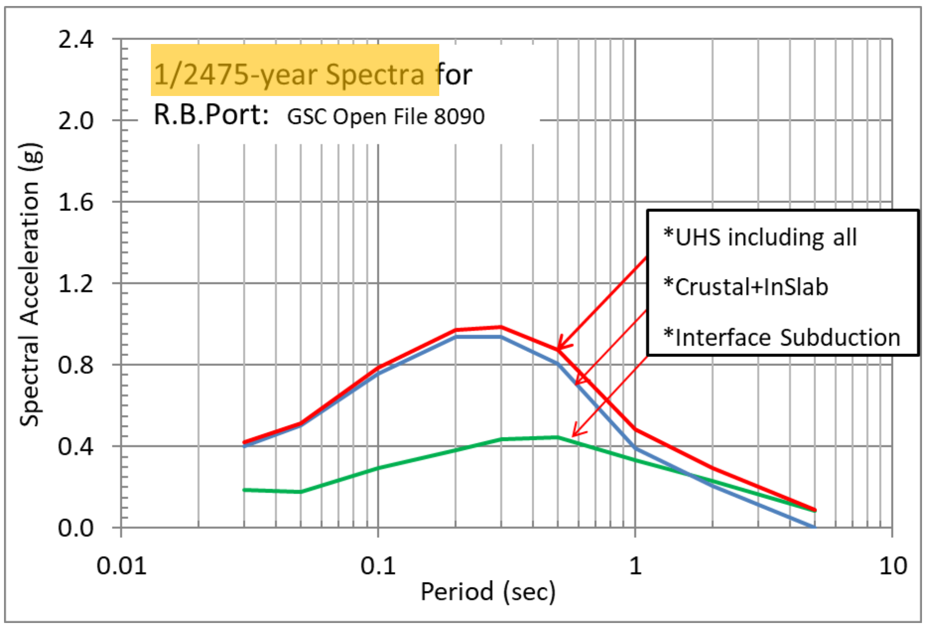
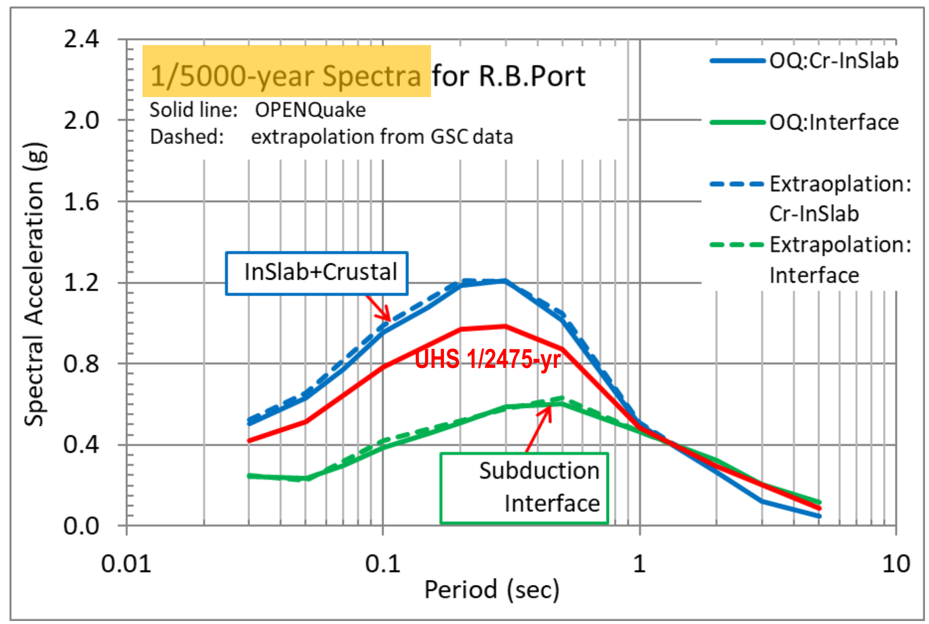
Spectra for 1/5000-yr Level (1%/50 years) and 10,000-yr when required, extrapolation vs. OpenQuake

GSC Grid pt. 34101 near the Roberts Bank Port

- Spectra for Subduction Interface (M9) - Green
- Spectra for Non-Interface (i.e., Crustal + InSlab) –Blue
- Total combined all source Uniform Hazard spectra (UHS) – Red





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PSPA Approach:
Probabilistic Seismic Performance Analyses

For example, to determine seismic displacement of a slope, say at 1/2475-yr level:

- Do not use all-source UHS 1/2475-yr: there is no applicable equations
- Use Mecedo et al (2017) Equation for ~M9 Interface at 1/2475-yr & 1/5000-yr
  - D (cm) $_{\sim M9}$ for Ts>0.05 s

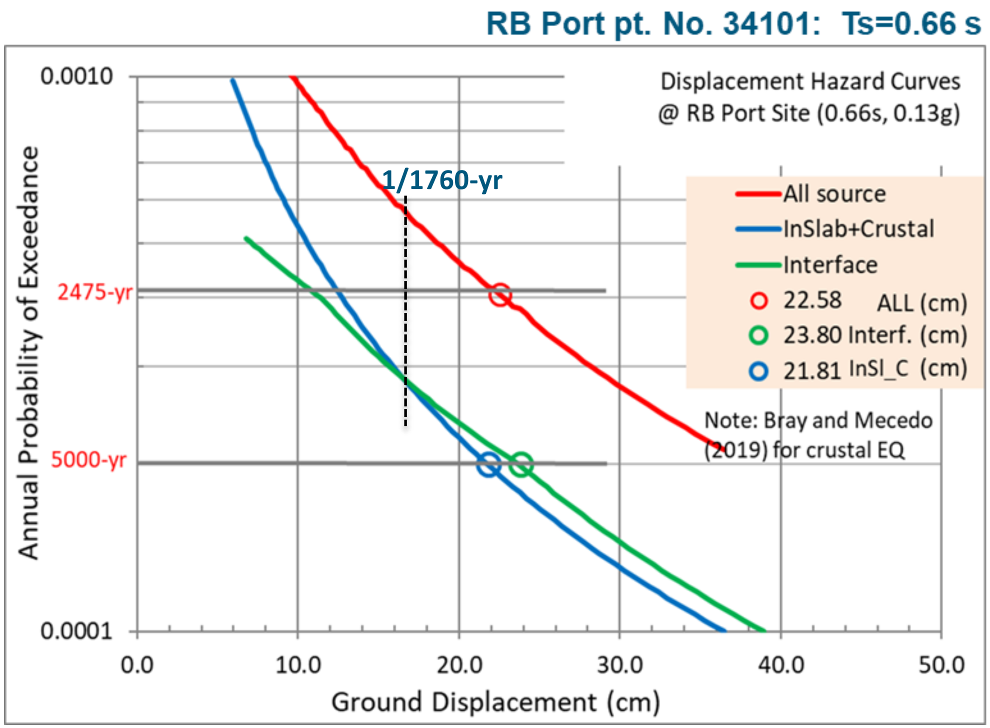
$$Ln(D) = -6.97 - 3.045Ln(k_y) - 0.328\left(Ln(k_y)\right)^2 + 0.448Ln(k_y)Ln(Sa(1.5T_s)) + 2.605Ln(Sa(1.5T_s)) - 0.233\left(Ln(Sa(1.5T_s))\right)^2 + 1.407T_s + 0.643M \pm \varepsilon \quad (4)$$

- Use Bray and Mecedo (2019) $_{\text{updated from 2007}}$ for ~M7 non-Interface earthquakes:
  - D (cm) $_{\sim M7}$ (a1, a2, a3 are constants):

$$\begin{aligned} Ln(D) = {} & a1 - 2.482Ln(k_y) - 0.244(Ln(k_y))^2 \\ & + 0.344Ln(k_y)Ln(S_a(1.3T_s)) + 2.649Ln(S_a(1.3T_s)) \\ & - 0.090(Ln(S_a(1.3T_s)))^2 + a2T_s + a3(T_s)^2 \\ & + 0.603M_w \pm \varepsilon_1 \end{aligned} \quad (3a)$$

-
- D (cm) $_{M9+M7}$ using the PSPA approach, i.e., adding probability for D(cm)$_{\sim M9}$ and for D(cm)$_{\sim M7}$
  - D (cm) $_{M9+M7}$ = D(cm)$_{\sim M9}$ = D(cm)$_{\sim M7}$
  - Probability: $P_{M9+M7} = P_{\sim M9} + P_{\sim M7}$
  - For 1/2475-yr displacement: annual P = 1/2475 = 0.000404

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



Legend:

Red - All source
Green – Interface ~M9
Blue – InSlab/Crustal ~M7

At 22.58 cm:

$P_{red} = P_{blue} + P_{green}$

$= 0.00019 + 0.00021$

$= 0.000400$

Note: blue and green lines cross at:

$P_{blue} = P_{green} = 0.000284$

$P_{red} = 0.000568$

Observations:

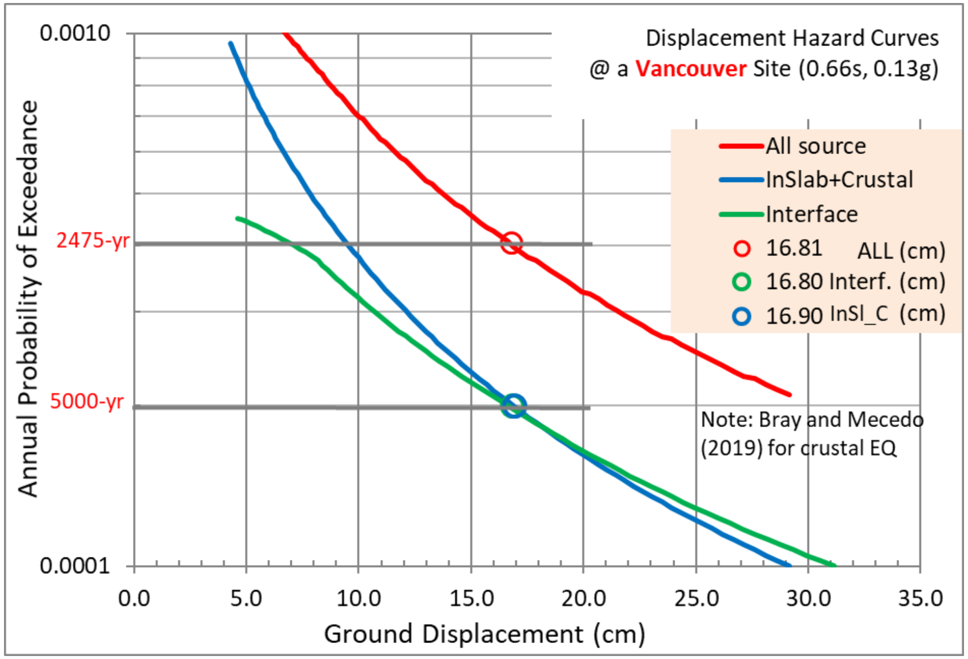
- $D(cm)_{\sim M7} \approx D(cm)_{M9+M7} \approx D(cm)_{\sim M9}$

At D = 22.58 cm

- $P_{\sim M7} \approx 0.5 * P_{M9+M7}$
- $P_{\sim M9} \approx 0.5 * P_{M9+M7}$

Note: For 1/1760-yr, "≈" becomes "="

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



Observations:

- $D(cm)_{\sim M7} \approx D(cm)_{M9+M7} \approx D(cm)_{\sim M9}$

At D = 16.81 cm

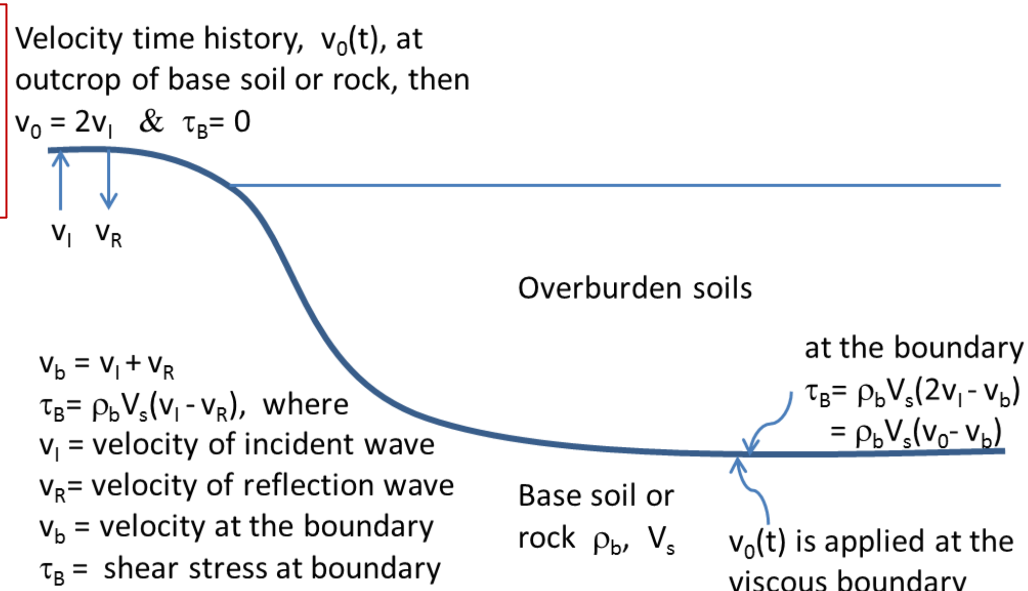
- $P_{\sim M7} \approx 0.5 * P_{M9+M7}$
- $P_{\sim M9} \approx 0.5 * P_{M9+M7}$

For Vancouver site: "≈" becomes "=" at 1/2475-yr

VERSAT dynamic analyses (1D & 2D) with elastic base

- **VERSAT dynamic analyses (1D & 2D) with elastic base (or compliance base, or viscous base boundary) by applying Outcropping Velocity Time History (TH) as Input ground motion.**
- **Figure 8 the elastic base model with a viscous boundary in VERSAT technical manual (2019)**

Surface outcropping motions on firm ground with Vs30 of 360 - 760 m/s: Applicable for GSC (2015) seismic hazard values



Within motions at firm ground model base are different from the outcropping motions, likely lower.

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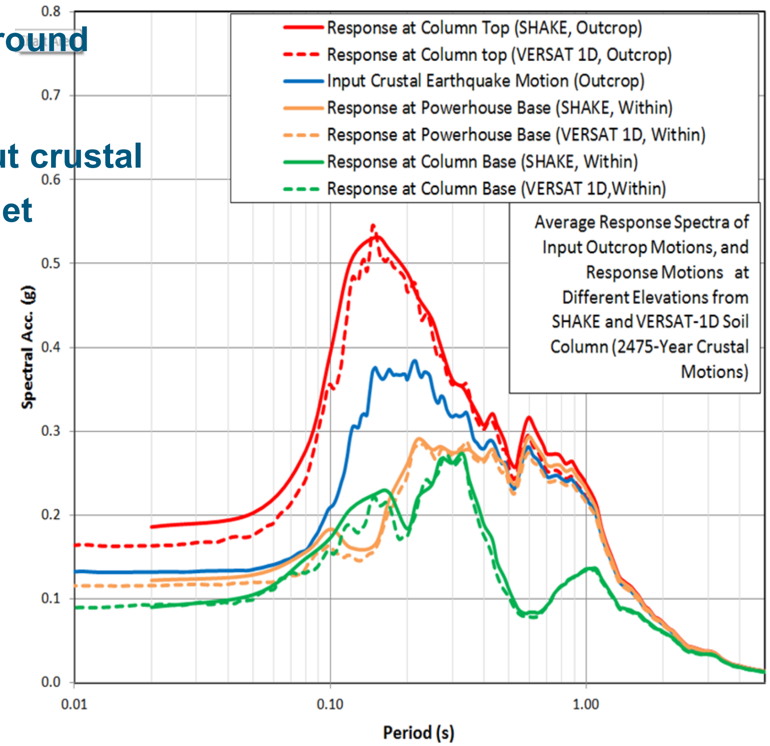
VERSAT dynamic analyses (1D & 2D) with elastic base

Comparison SHAKE & VERSAT Results:

- For ground motion response of site with an elastic base
- A site near Bridge River BC where firm ground was modelled at 50 m depth with V_s=450 m/s
- Low-median level of earthquake shaking with firm-ground outcrop PGA of 0.14 g
- Spectra shown in the graph are average using 7 input crustal earthquake motions, linearly scaled to the same target spectrum.

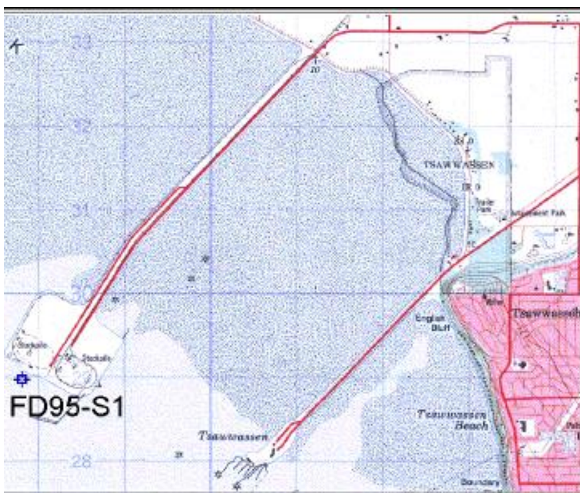


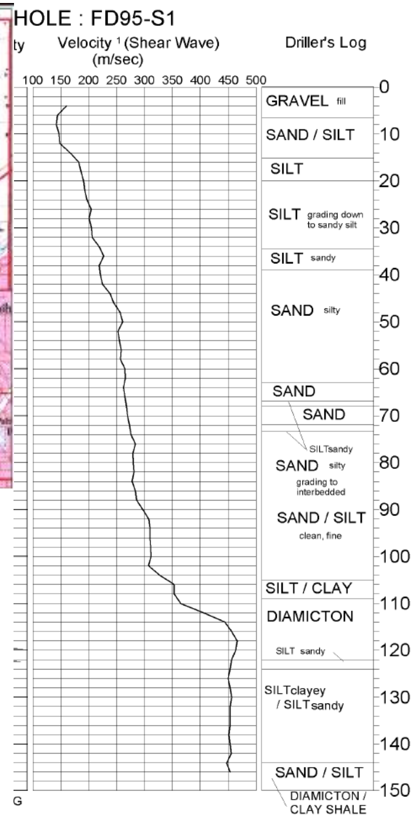
Summary: Results from VERSAT and SHAKE agreed very well, for motions both at the base and at top of the 50 m thick soil column

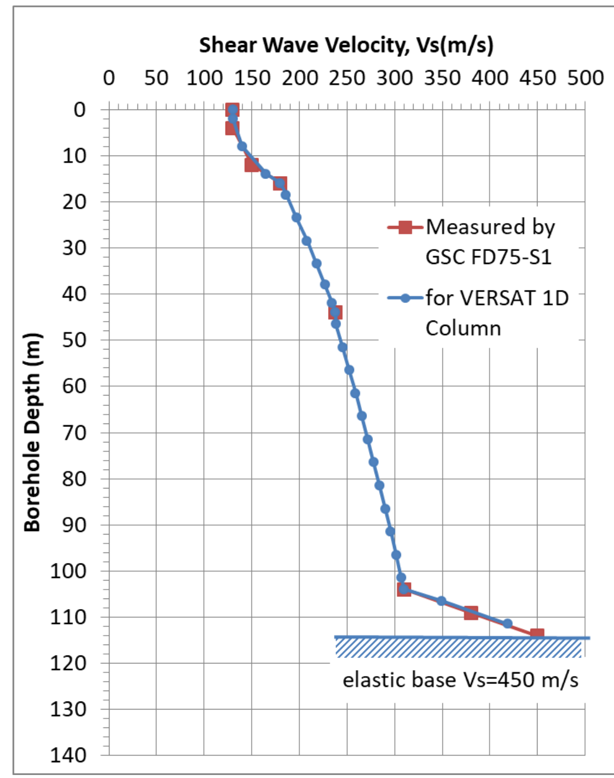
Reference: VERSAT technical manual

Site Response Analyses: VERSAT 1D Soil Model

- 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.







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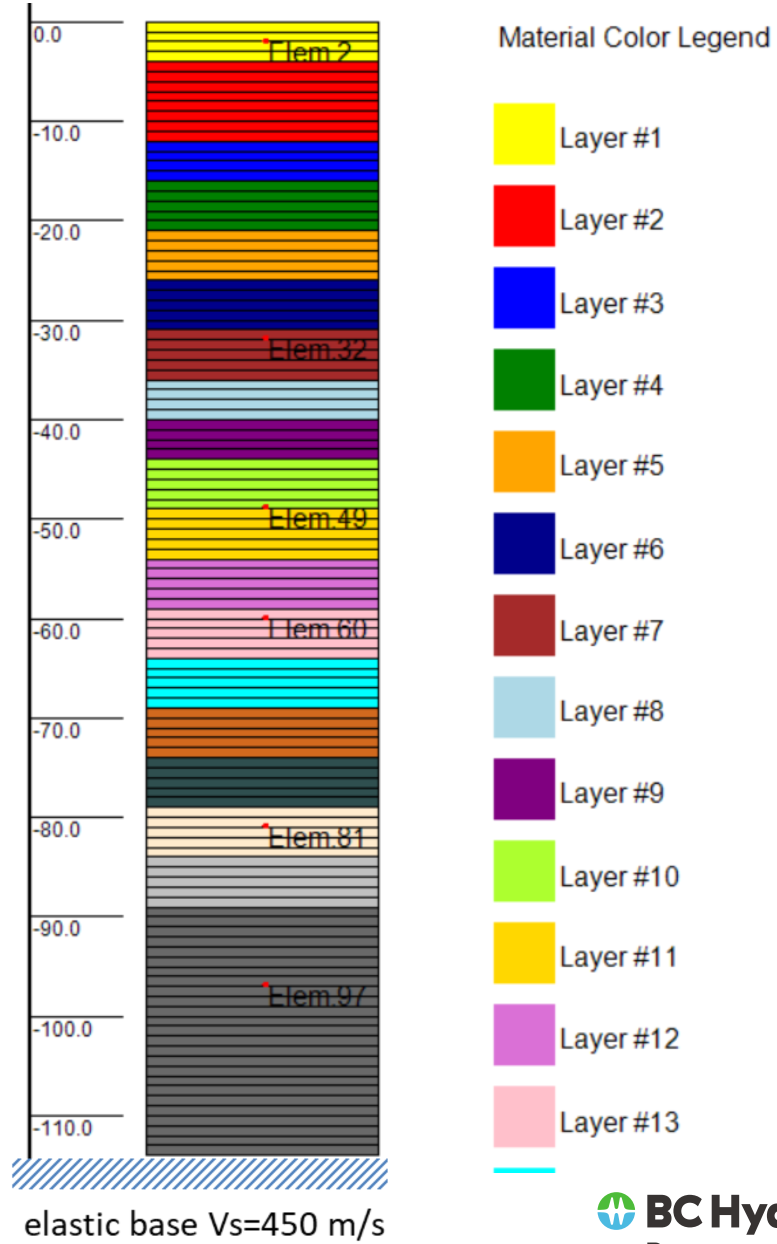
Site Response Analyses: VERSAT 1D Soil Model

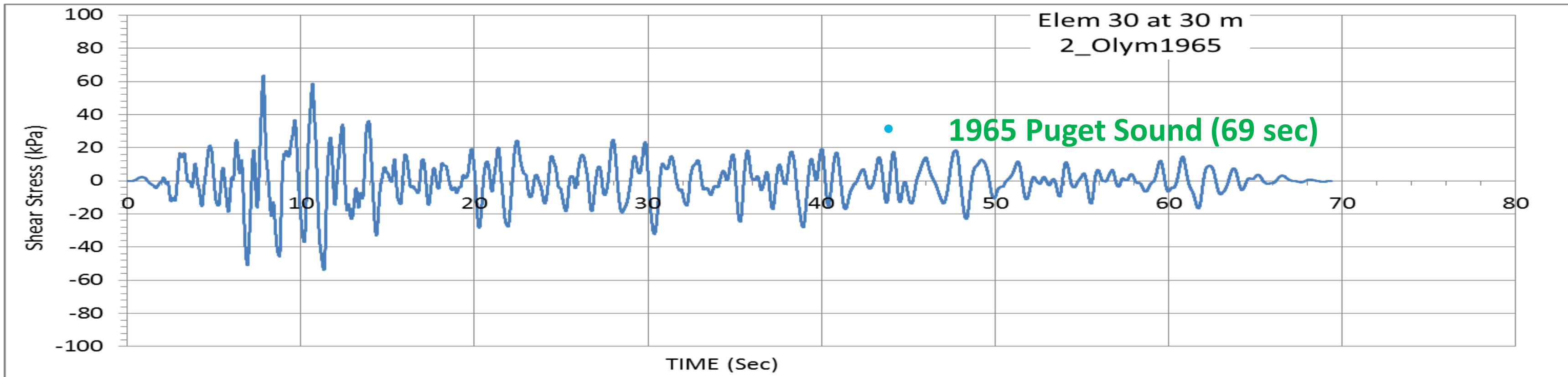
- Using nonlinear finite element time history analyses (VERSAT-1D, Wutec 2019)
- VERSAT 1D Soil Model: 23 layers used in the model for a total of 114 soil elements (1 m thick each); elastic base with V_s=450 m/s; outcropping velocity TH applied to the model

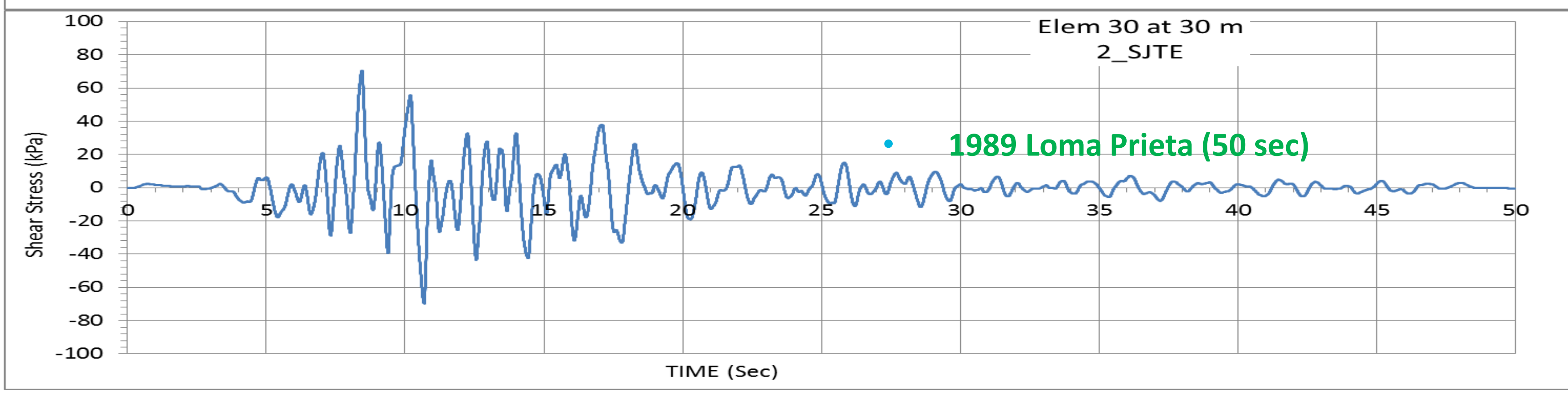


Site Response Analyses: VERSAT 1D Soil Model

VERSAT 1D Results:

- Cyclic Shear Stress Model for Liquefaction
- Shear stress THs for Elem-30 at 29.5 m depth (2475-yr, InSlab/Crustal)





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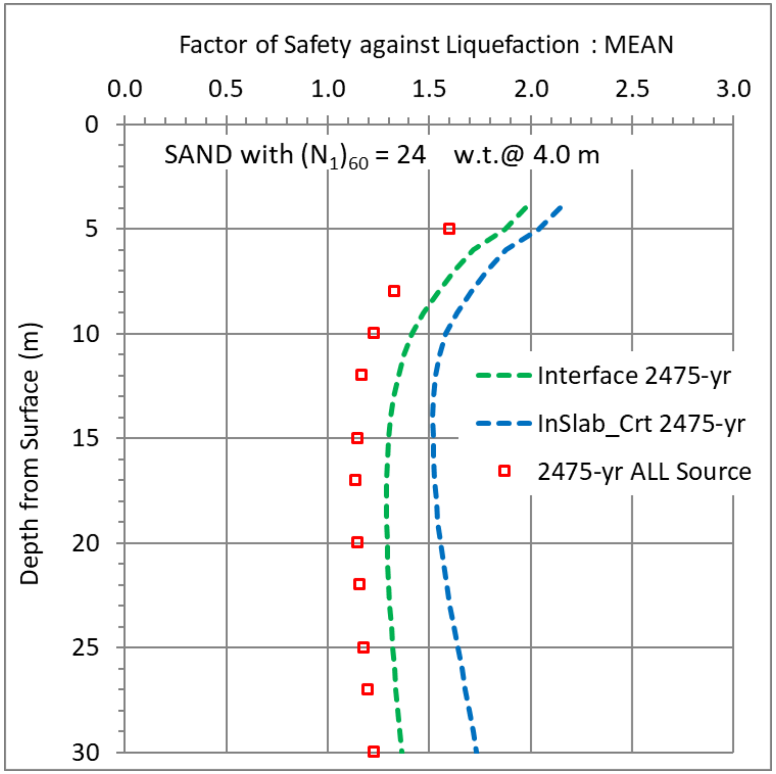
Factors of Safety (FoS) against liquefaction Deterministic analysis assuming $N_{1.60}$=24

Result 1/2475-yr (Wu 2017)

- using 11 EQ records for each EQ source
- Method B “all Cumulated” for 1/2475-yr all source



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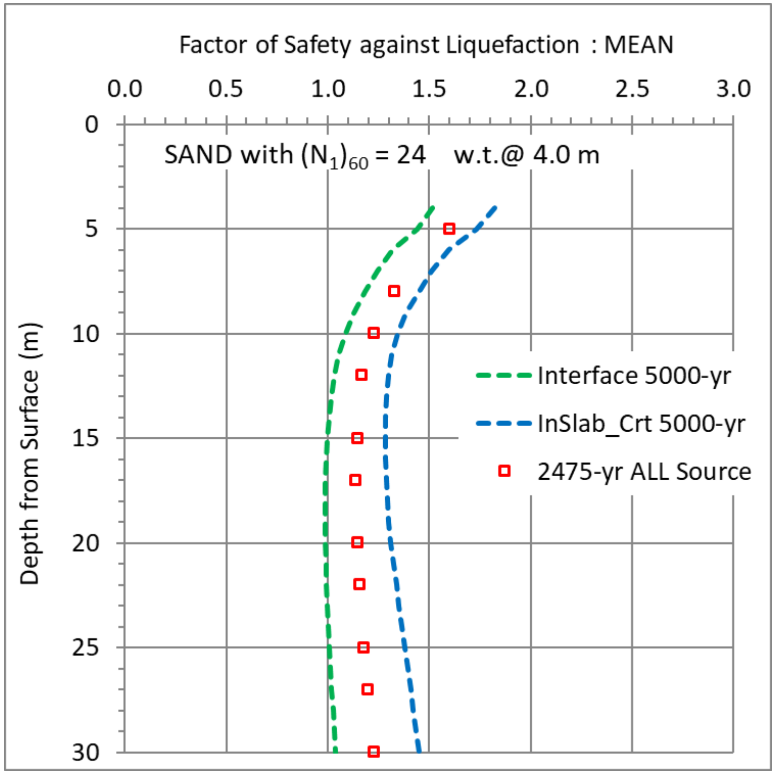
Factors of Safety (FoS) against liquefaction Deterministic analysis assuming $N_{1.60}$=24

Result 1/5000-yr (Wu 2017)

- **using 11 EQ records for each EQ source**
- **Method B "all Cumulated" for 1/2475-yr all source**



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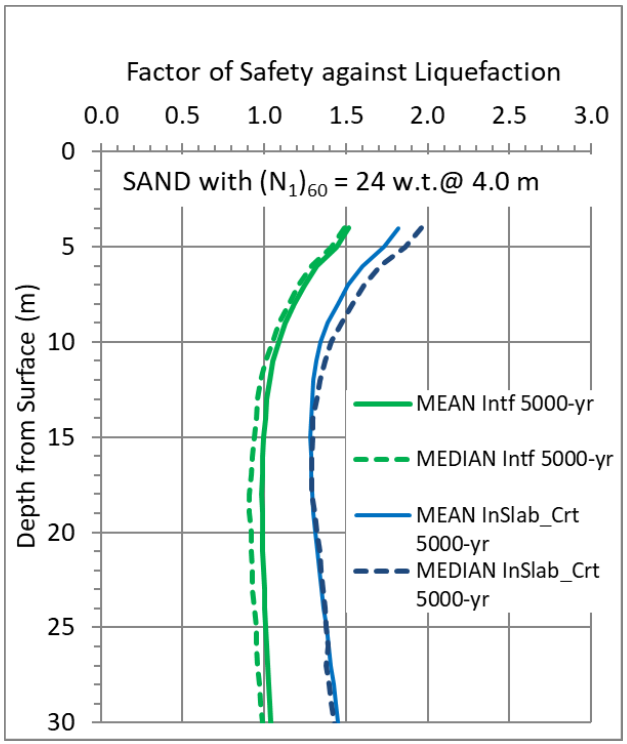
Factors of Safety (FoS) against liquefaction
Deterministic analysis assuming $N_{1.60}$=24

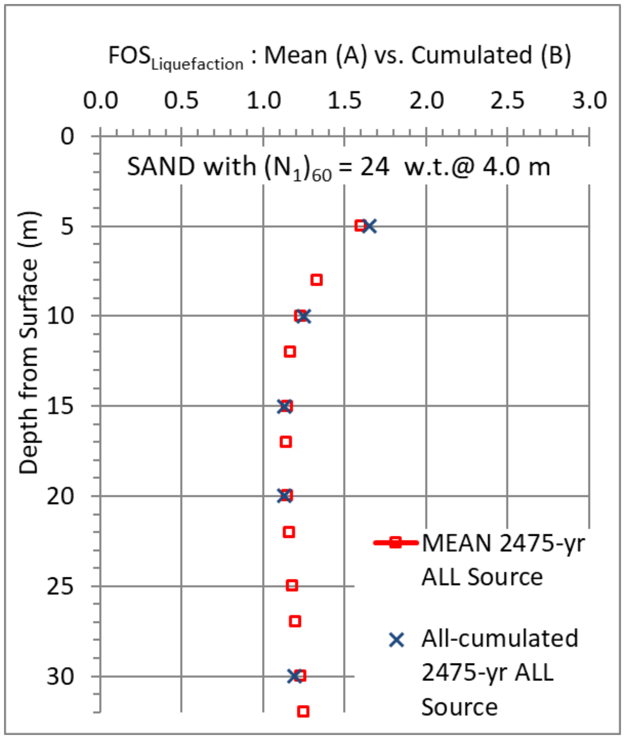
1/5000-yr: Mean vs. Median (Wu 2017)

- using 11 EQ records for each EQ source



Method A vs. Method B (Wu 2017)

- using 11 EQ records for each EQ source



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PSPA for displacements, FS_{liq}, or any quantities Probability of 2%/50-yr

Probability P_{M9+M7}

- $= P_{\sim M7} + 0$; where no contribution from M9 (in Calgary, etc)
- $= 0 + P_{\sim M9}$; where no/little contribution from M7 (in Pacific Ocean)
- $= P_{\sim M7} + P_{\sim M9}$; In the lower Mainland, near half-half each

In the Lower Mainland for 1/2475-yr:

$1 \neq 1 + 1$;

$1 = 0.5 + 0.5$

Therefore, 1/5000-yr for each EQ source is a good bet to start.

Probability of Liquefaction (P_f), reliability index (β)

Reliability of soil against liquefaction $= 1 - P_f$

Reliability

- A). Sampling method, a Monte Carlo simulation (10^6 samples)
- B). Approximate algorithms, FORM, SORM (Foschi et al 2017)

A). Sampling method: $P_f = \frac{N_f}{N}$

- **A subject (or system) is comprised of one or many stochastic (or random) variables.**
- **Each variable (or each collection of variables) has its own statistical distribution.**
- **N_f = number of failed samples**
- **N = number of total sample; N = 3465 samples in this study**
- **In this study, failed sample means: $FS_{liq} \leq 1.0$ (i.e., $crr_{15} \leq csr_{15}$)**

Probability of Liquefaction (P_f), reliability index (β)

Reliability of soil against liquefaction = $1 - P_f$

Reliability

- A). Sampling method, a Monte Carlo simulation (10^6 samples)
- B). Approximate algorithms, FORM, SORM (Foschi et al 2017)

A). continued**...**

- Sampling method: $\beta = (\mu_{FS} - 1) / \sigma$
- where μ_{FS} is the mean of subject samples (i.e., average of the 3465 samples)
- σ is the standard deviation of the 3465 samples.

B). First Order Reliability Method (FORM): Reliability index (β): $P_f = \Phi(-\beta)$

where Φ is the standard normal distribution function

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Probability of Liquefaction (P_f), reliability index (β)

- sandy layer from 5 to 12 m depth under 1/5000-yr non-Interface ground motions

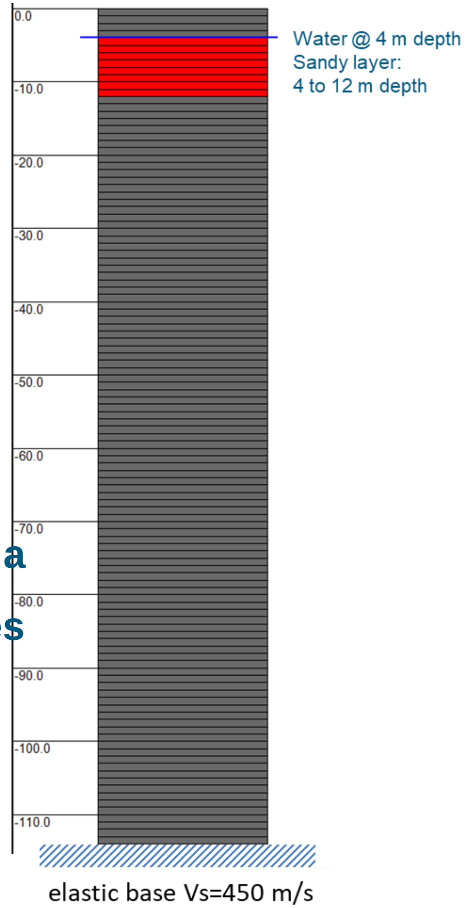
Method B). FORM (Foschi 2011; Foschi et al. 2017)

Performance function **G = Capacity – Load**

$$G = crr_{15}(N_{1\_60}, CRR_{15}, K_\sigma) - csr_{15}(V_s, \text{record}, \alpha)$$

Where,

- **crr_{15} – cyclic shear stress ratio (over at-depth σ_v') to cause liquefaction in 15 cycles**
- **csr_{15} – cyclic shear stress ratio (over at-depth σ_v') caused by a earthquake ground motion (the record), corrected to 15 cycles**
- **Stochastic variables: EQ record, α, N_{1_60}, CRR_{15}**
- **Deterministic variables: V_s, K_σ**
- **Conventional $FS_{liq} = crr_{15} / csr_{15}$**



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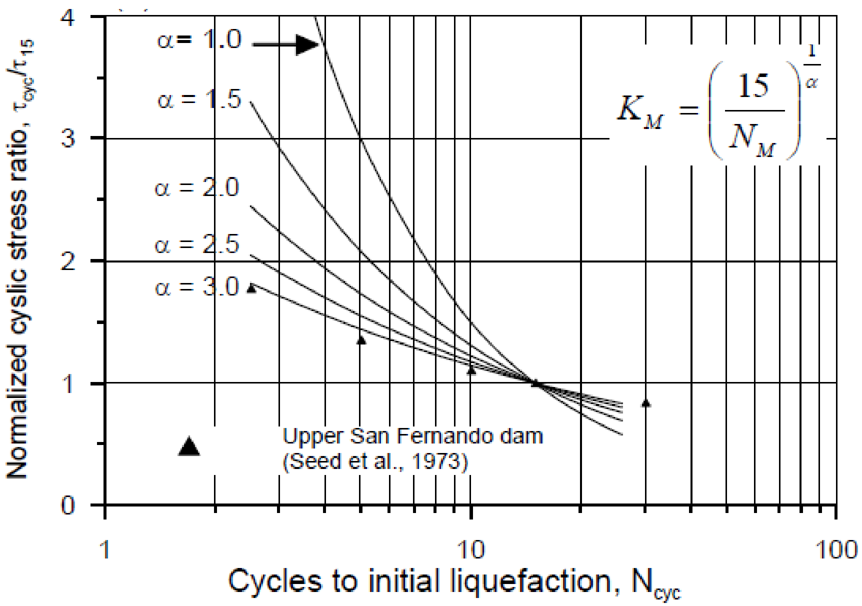
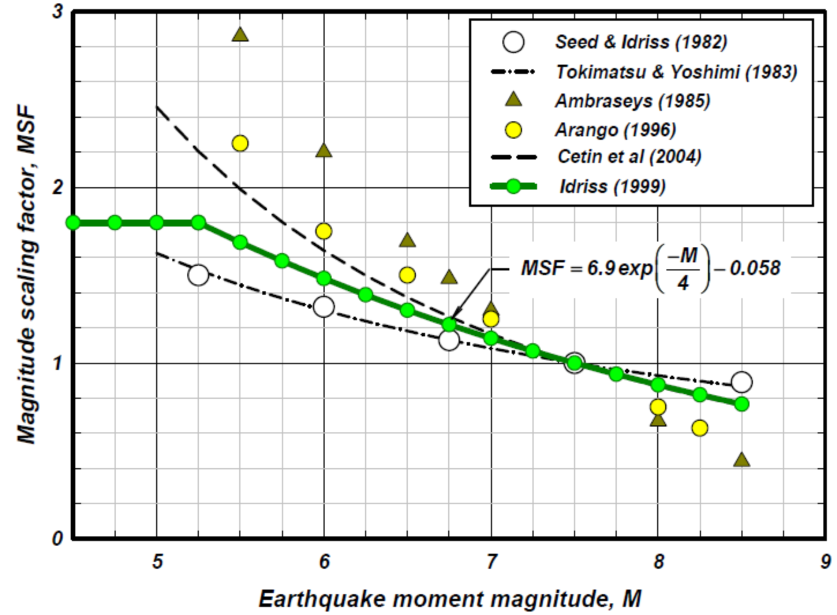
LOAD side:
Earthquake magnitude correction: α factor

Wu (2001) – used in VERSAT



Wu (2001) Can. Geotech. J. 38: 1–15

Idriss and Boulanger (2010)



$$MSF = \frac{CRR_M}{CRR_{M=7.5}} = \left(\frac{N_{M=7.5}}{N_M}\right)^b$$

- CRR_M = CRR at a given magnitude
- CRR_M =7.5 = CRR at M=7.5
- $N_{M=7.5}$ = number of uniform cycles for M = 7.5
- N_M = number of uniform cycles for a given magnitude
- b = fitting parameter

LOAD side: Earthquake ground motions

1). K_M (or MSF) factors applied in probability analysis with unequal weight

	Fitting parameter	Cetin et al. 2004	Idriss 1999	Seed and Idriss, 1982
VERSAT-1D, 2D (Wu 2001)	α	2.0	2.85	3.6
Idriss and Boulanger (2010)	b	0.5	0.35	0.28
Probability Weight (Σ=1)		0.3	0.4	0.3

Note: VERSAT $\alpha = \frac{1}{b}$

2). 21 EQ records with an equal weight (Σ=1.0)

Record #	Short name	Probability Weight	Record #	Short name	Probability Weight	Record #	Short name	Probability Weight
1	c-Abbar	0.0476	8	c-LDM	0.0476	15	c-UCSC	0.0476
2	c-CHL	0.0476	9	c-PUL	0.0476	16	c-Yoita	0.0476
3	c-CPE	0.0476	10	c-SJTE	0.0476	17	s-Gigh	0.0476
4	c-Dayhook	0.0476	11	c-SSU	0.0476	18	s-Myg13	0.0476
5	c-IZT	0.0476	12	c-TAB	0.0476	19	s-Olym1949	0.0476
6	c-K-Nish	0.0476	13	c-TCU071	0.0476	20	s-Olym1965	0.0476
7	c-Lamont	0.0476	14	c-TCU129	0.0476	21	s-Olym2001	0.0476

Note: c - crustal EQ record, s - InSlab EQ record

LOAD side input: 21 Ground Motion records scaled for 1/5000-yr Non-Interface spectra (PGA=0.523 g)

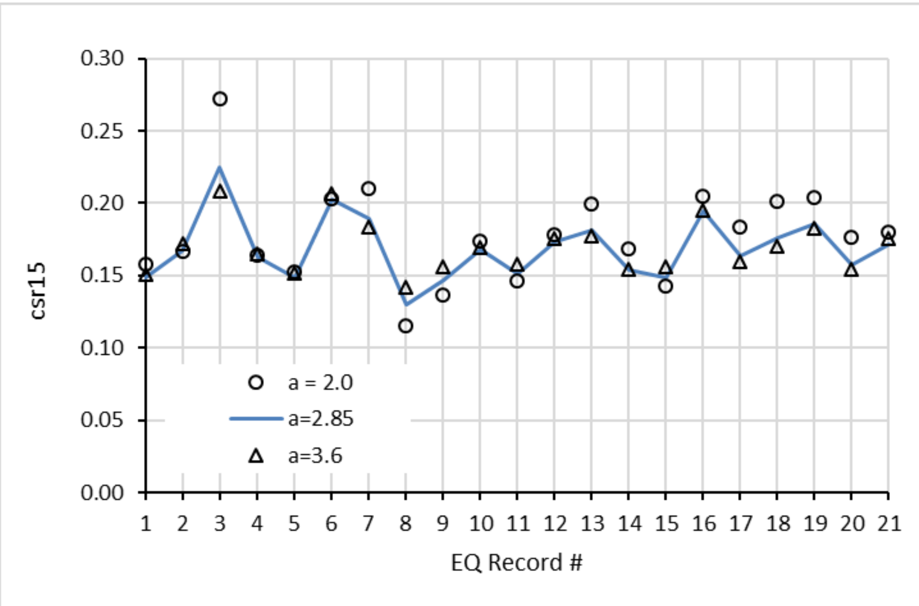
- **16 Crustal EQ records: AVG PGA = 1.29*0.434 = 0.560 g**
- **5 InSlab EQ Records: AVG PGA= 1.29*0.430= 0.555 g**

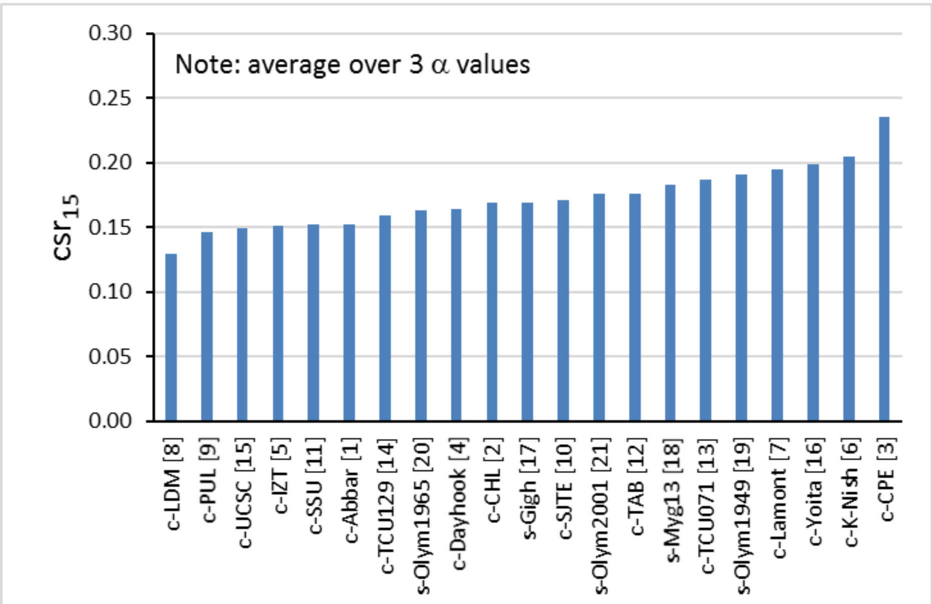
Ground Motions Linearly Scaled for GSC (2015) 2475-yr InSlab/Crustal and Subduction Interface Spectra for R.B. Port - pt. 34101 (A scale factor of 1.29 is further applied to below table for the 5000-yr ground motions)

	Earthquake			Recording Station	N	dt	Duration	PGA	PGV	PGD	Arias Int.	5%-95%
Set	Name	Date	Magnitude		points	[sec]	(sec)	[g]	[m/s]	[m]	[m/s]	[sec]
Crustal Ground Motions								0.434				
1	Manjil, Iran	6/20/1990	7.37	Abbar	2300	0.02	46.0	**0.391**	0.415	0.188	4.7	29.08
2	Northridge, CA	17-Jan-1994	6.69	CHL Chalon Rd	3107	0.01	31.1	**0.354**	0.315	0.060	1.7	9.0
3	Imperial Valley, CA	15-Oct-1979	6.5	CPE_Cerro Priet	6382	0.01	63.8	**0.364**	0.25	0.113	5.7	30.0
4	Tabas, Iran	16-Sep-1978	7.35	Dayhook	1050	0.02	21.0	**0.495**	0.343	0.228	3.4	11.34
5	Turkey, Kocaeli	17-Aug-1999	7.51	Izmit	3000	0.01	30.0	**0.342**	0.574	0.358	1.8	13.3
6	Chuetsu-oki, Japan	16-Jul-2007	6.8	K.Nishiyamacho	6000	0.01	60.0	**0.426**	0.368	0.065	2.1	11.19
7	Duzce, Turkey	12-Nov-1999	7.14	Lamont 531	4150	0.01	41.5	**0.312**	0.339	0.200	2.6	14.89
8	Northridge, CA	17-Jan-1994	6.69	LA Dam	2658	0.01	26.6	**0.317**	0.469	0.239	1.3	6.5
9	San Fernando, CA	24-May-1905	6.61	PUL Pacoima Da	4172	0.01	41.7	**0.620**	0.288	0.064	2.0	7.26
10	Loma Prieta, CA	18-Oct-1989	6.93	SJTE Santa Teres	4999	0.01	50.0	**0.479**	0.493	0.404	4.0	10.1
11	Northridge, CA	17-Jan-1994	6.69	SSU Santa Susan	5725	0.01	57.3	**0.373**	0.257	0.103	2.2	7.36
12	Iran, Tabas	16-Sep-1978	7.35	TABas	1650	0.02	33.0	**0.386**	0.447	0.174	2.4	16.5
13	Chi-Chi, Taiwan	20-Sep-1999	7.62	TCU071	5040	0.01	50.4	**0.323**	0.279	0.094	3.4	24.0
14	Chi-Chi, Taiwan	20-Sep-1999	7.62	TCU129	7798	0.01	78.0	**0.582**	0.364	0.365	3.1	27.34
15	Loma Prieta, CA	18-Oct-1989	6.93	UCSC	2501	0.01	25.0	**0.862**	0.281	0.049	7.1	8.58
16	Chuetsu-oki, Japan	16-Jul-2007	6.8	Yoitamachi Yoita	6000	0.01	60.0	**0.311**	0.337	0.077	2.3	15.79
InSlab Ground Motions								0.430				
17	Washington Nisqually	28-Feb-2001	6.8	Gig Harbour, Fire Station	9900	0.01	99.0	**0.348**	0.323	0.136	2.4	23.5
18	Japan MiyagiOki	16-Aug-2005	7.2	MYG013	7992	0.01	79.9	**0.575**	0.415	0.049	5.6	21.5
19	Western Washington	13-Apr-1949	6.9	Olympia_1949 Highway Lab	7532	0.01	75.3	**0.351**	0.385	0.126	3.1	19.2
20	Washington Puget Sou	29-Apr-1965	6.7	Olym1965 Highway Lab	6939	0.01	69.4	**0.519**	0.319	0.114	3.0	20.8
21	Washington, Nisqually	28-Feb-2001	6.8	Olym2001 Highway Lab	8294	0.01	82.9	**0.355**	0.296	0.065	1.9	16.5

LOAD side output: csr_{15} (11.5 m depth) results from VERSAT : 21 records x 3 = 63

- **Record #3 – CPE gives the highest csr_{15} among the 21 records**
- **Record #8 – LA Dam gives the lowest csr_{15}**
- **On average, α = 2.0 gives higher csr_{15} than α =2.85 or 3.6**





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LOAD side: csr_{15} probability density function (PDF)

- csr_{15} distribution fits well in a normal distribution
- At 11.5 m depth, csr_{15} normal distribution line: μ_{csr15} = 0.1687 and σ = 0.020

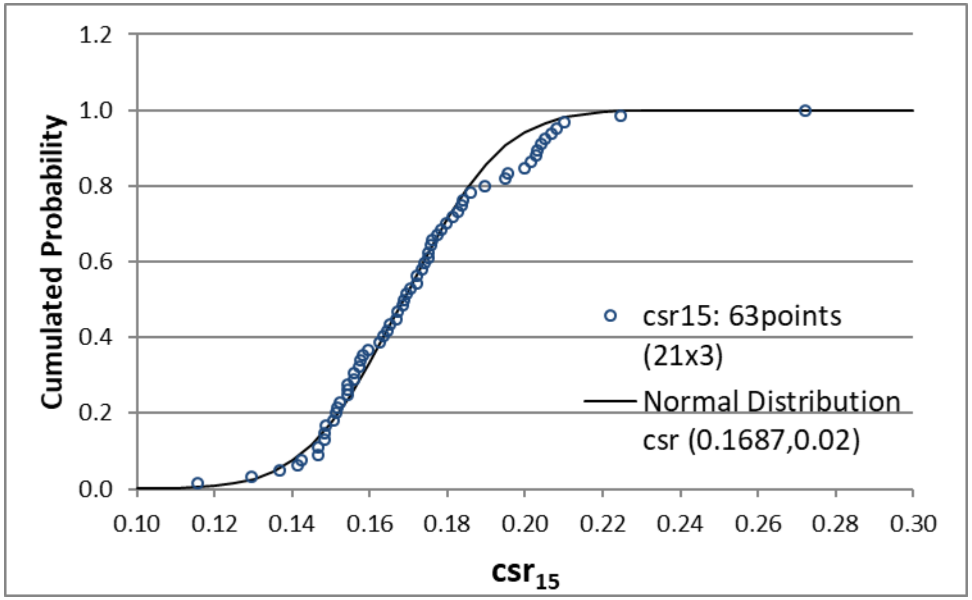


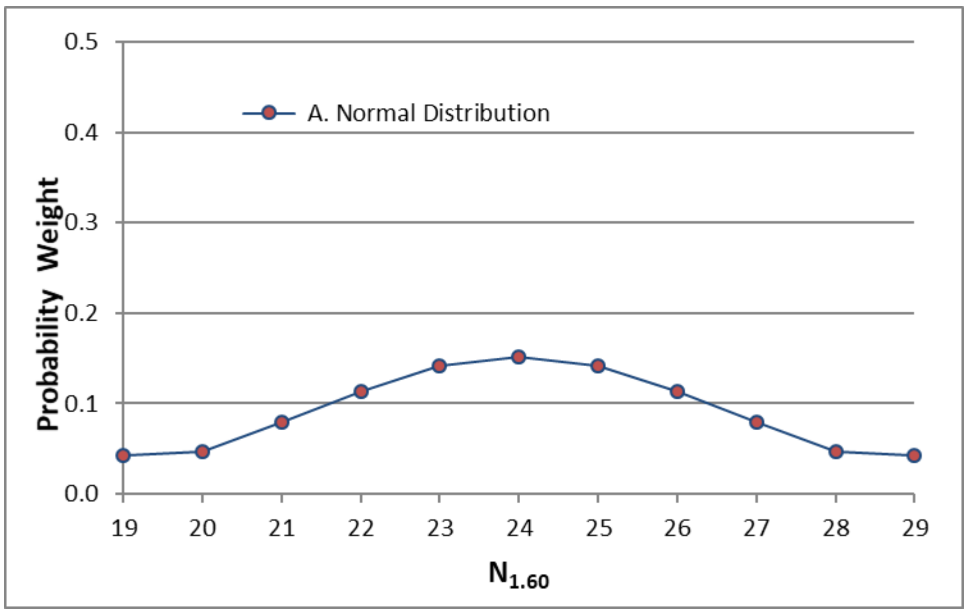
Figure A: csr_{15} Cumulative Probability Distribution Function (CDF)

CAPACITY: $N_{1.60}$ data for sandy layer (4 to 12 m depth)

- $N_{1.60}$ normal distribution centered at $N_{1.60} = 24$
- $N_{1.60}$ probability weight below (total Σ=1.0)

Disclaim: Purely Assumed.
Don't Use It in design works!

$N_{1.60}$	19	20	21	22	23	24	25	26	27	28	29	Σ
A. Normal Distribution	0.042	0.047	0.079	0.114	0.142	0.152	0.142	0.114	0.079	0.047	0.042	**1.00**



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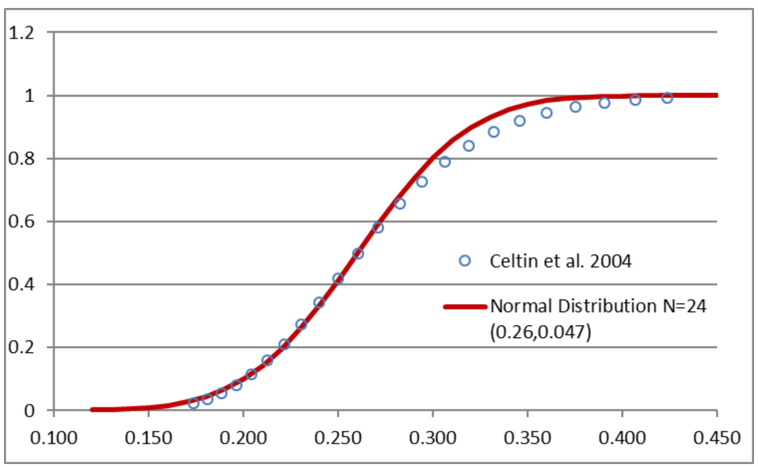
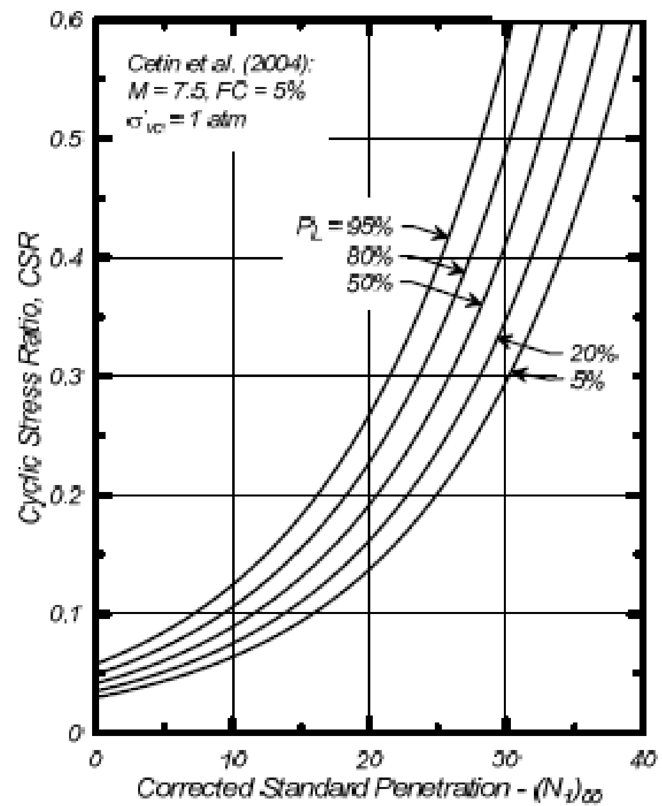
CAPACITY: crr_{15} for sandy layers: 4 to 12 m depth

Disclaim: Purely Assumed.
Don't Use It in design works!

- For each $N_{1.60,}$ applying Cetin et al (2004) probabilistic correlation of CRR_{15} with $N_{1.60}$
- For $N_{1.60}$ = 24, CRR_{15} normal distribution is centered at 0.26 with σ = 0.047

Cetin et al. (2004)	5%	20%	50%	80%	95%
Probability Weight	0.11	0.23	0.33	0.23	0.10





Note: use of Toprak et al (1999) would result in more scattered CRR_{15} distribution than Celtin et al (2004)

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CAPACITY: crr_{15} probability density function (PDF)

- crr_{15} distribution fits well in a normal distribution
- At 11.5 m depth, crr_{15} normal distribution line: μ_{crr15} = 0.2395 and σ = 0.066 (Set-A)

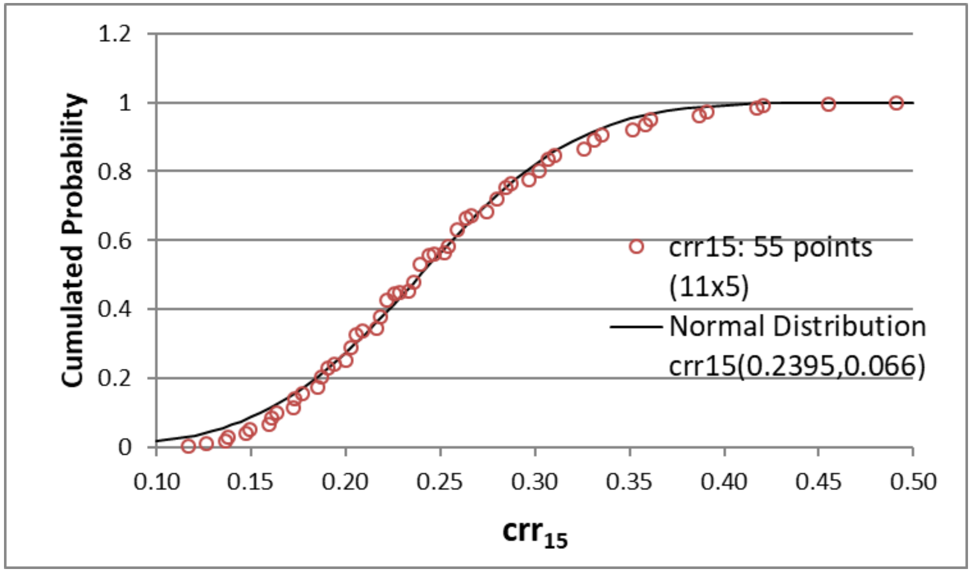

Figure B: crr_{15} Cumulative Probability Distribution Function (CDF)

CAPACITY – Load:

crr_{15} – csr_{15} Probability Density Function (PDF)

- csr_{15} by using the 21 EQ records are less scattered (less deviation, low σ) than crr_{15}
- crr_{15} for liquefaction resistance has more deviation and high σ; curve is wider and flatter
- Both crr_{15} and csr_{15} can be characterized using a normal distribution

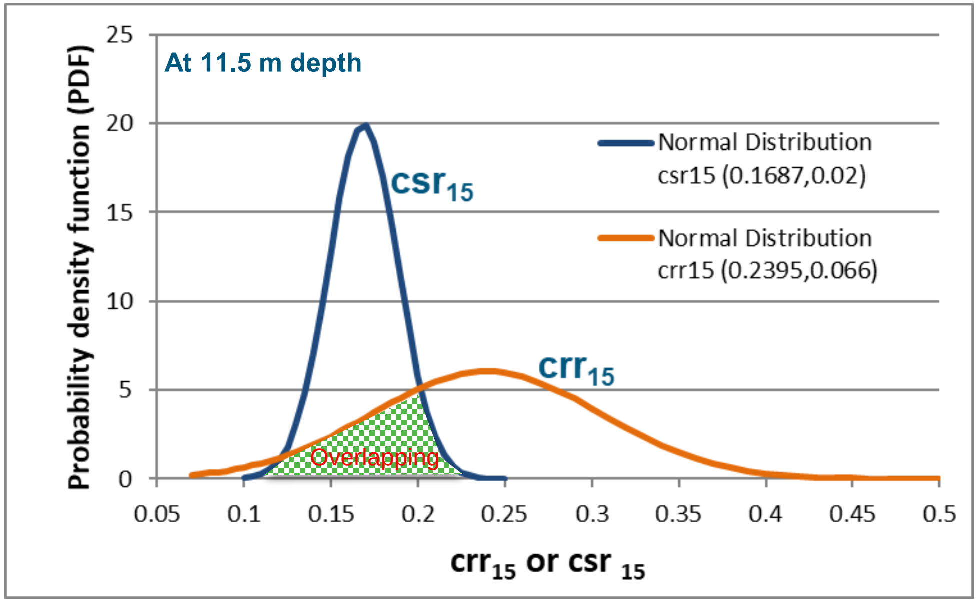

Figure C: crr_{15} and csr_{15} Probability Density Function (PDF)

Probability of Liquefaction (P_f), reliability index (β)

Method B). First Order Reliability Method (FORM) (Rackwitz 1978; Fosci 2011; Fosci et al. 2017)

- using the Lines in Figure A and Figure B

$$\beta = \frac{\mu_{crr15} - \mu_{csr15}}{\sqrt{\sigma_{crr15}{}^2 + \sigma_{csr15}{}^2}}$$

Where at 11.5 m depth

- μ_{crr15} – w. mean (= median) of the crr_{15} distribution, 0.2395
- μ_{csr15} – w. mean (= median) of the csr_{15} distribution, 0.1687
- σ_{crr15} – standard deviation of the crr_{15} distribution, 0.066
- σ_{csr15} – standard deviation of the csr_{15} distribution, 0.020

i.e.

σ_G = 0.069

β = 1.026

P_f = 0.152

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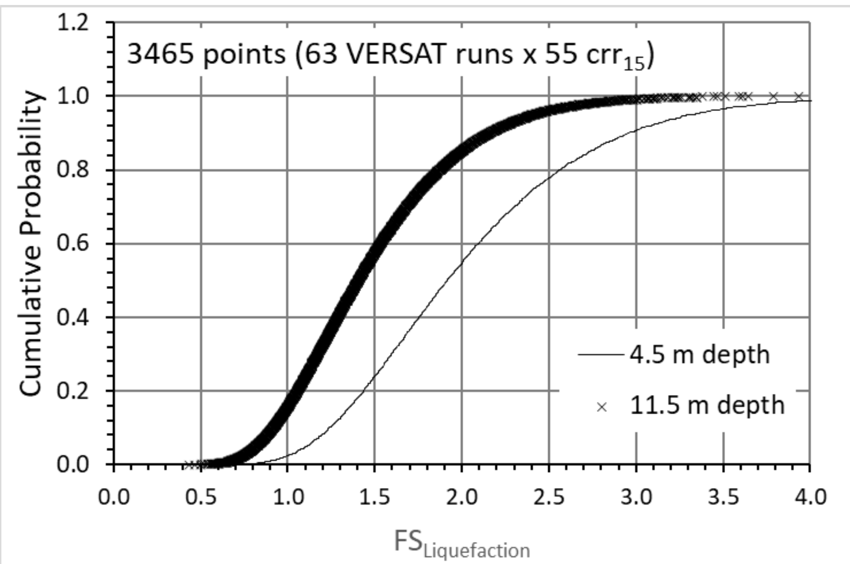
Probability of Liquefaction (P_f), reliability index (β)

Method A). Sampling method

- using the data points in Figure A and Figure B

- No correlation between crr_{15} and csr_{15}: Coefficient of Variation COV = 0
- VERSAT-1D site response runs: 21 records x 3 α factors (63 samples of LOAD)
- Soil (4 to 12 m depth) N_{1_60} & CRR_{15} combinations: 11 x 5 (55 samples of CAPACITY)
- Total # of samples: 63 x 55 = 3465 (no need to run 3465 VERSAT analyses since COV=0)



Soil Depth	4.5 m	11.5 m
w. Median Fs_{liq}	1.92	1.40
w. Mean, μ_{FS}	2.03	1.48
S. deviation, σ	0.69	0.50
Reliability β	1.49	0.97
$P_f = \frac{N_f}{N}$	0.024	0.157

Note: $\beta = (\mu_{FS} - 1) / \sigma$

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Probability of Liquefaction (P_f), reliability index (β)

Deterministic Approach

for $N_{1.60}$ = 24 with CRR_{15}=0.26

Equation: $30 / V_{s30} = \Sigma H(i) / V_s(i)$ see Table

PGA at Class C site surface: 0.523g for 1/5000-yr Non-interface

PGA at (R.B. Port) Class E site surface: a_{max} = 0.387g

At 11.5 m (7.5 m below water): σ_v'=140.9 kPa, σ_v=214.5 kPa

$$CSR_{M,\sigma_v'} = 0.65 \frac{\sigma_v}{\sigma_v'} \frac{a_{max}}{g} r_d$$

$csr_{15} = csr_{M7.5} = csr_{M7.0} / K_M$ (i.e., earthquake M=7.0)

$crr_{15} = CRR_{15} * K_\sigma$

VERAST-1D model			
Depth	Vs (m/s)	H (m)	elape t (s)
0	130		
4	130	4	0.0308
12	150	8	0.0571
16	180	4	0.0242
21	186	5	0.0273
26	197	5	0.0261
31	208	5	0.0247
V_{s30}=	163	**31**	
Site Class E			
NBCC Table 4.1.8.4.H Fac(PGA) =			**0.74**

Method	Cetin et al., 2004	Idriss, 1999	Seed and Idriss, 1982
K_M	1.22	1.15	1.12
Weight	0.3	0.4	0.3
			Weighted average, K_M = 1.16

Quantity	Assuming Class E site		VERSAT @ depth	
	11.5 m	4.5 m	11.5 m	4.5 m
a_{max}	0.387	0.387	-	-
r_d	0.835	0.954	-	-
csr_M	0.3198	0.2553	-	-
csr_{15}	0.2752	0.2197	0.1687(1)	0.1342(2)
K_σ	0.921	1.000	0.921	1.0
crr_{15}	0.2394	0.2600	0.2395	0.26
FS_{liq}	0.87	1.18	1.420	1.937

(1) w. Average =0.1722
(2) w. Average =0.1370
w. median used in Table

Comparing results:

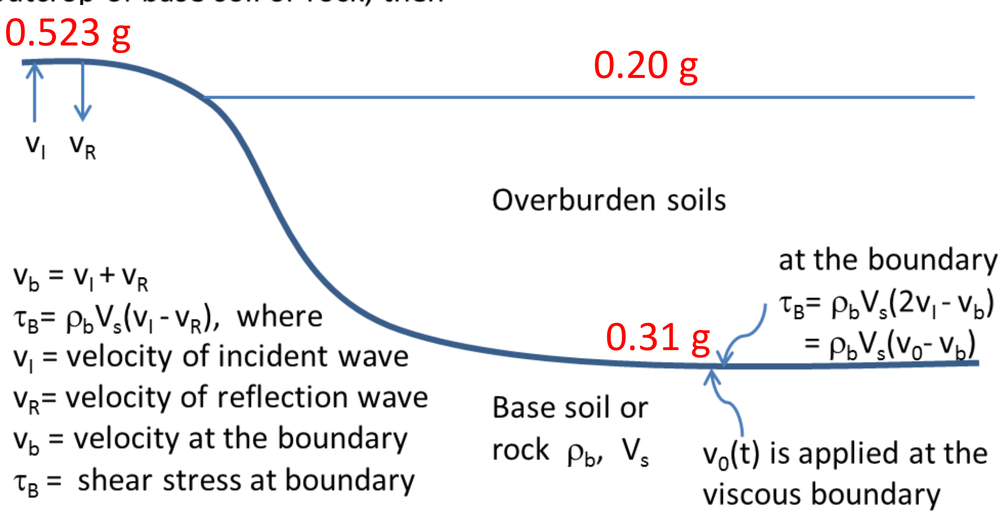
- Large difference FS_{liq}=1.42 by VERSAT
- FS_{liq}= 0.87 for Class E site. Why? Because
- this is a Class F site and requires dynamic analysis !

Probability of Liquefaction (P_f), reliability index (β)

Class F Site:

- **More than 30 m thick of soils with V_s <360 m/s**
- **At R.B. Port, there 106 m thick of soft to medium stiff soils**

Velocity time history, $v_0(t)$, at outcrop of base soil or rock, then



$v_b = v_I + v_R$

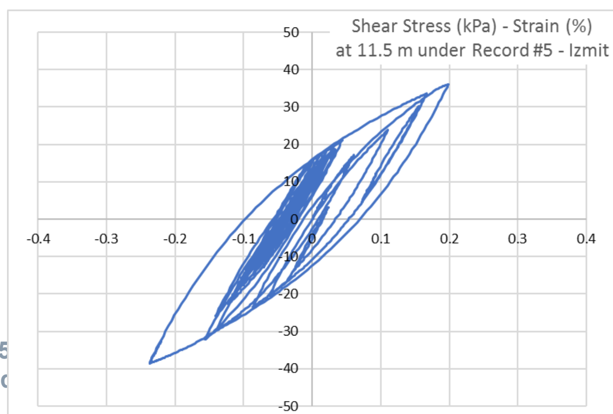
$\tau_B = \rho_b V_s (v_I - v_R)$, where

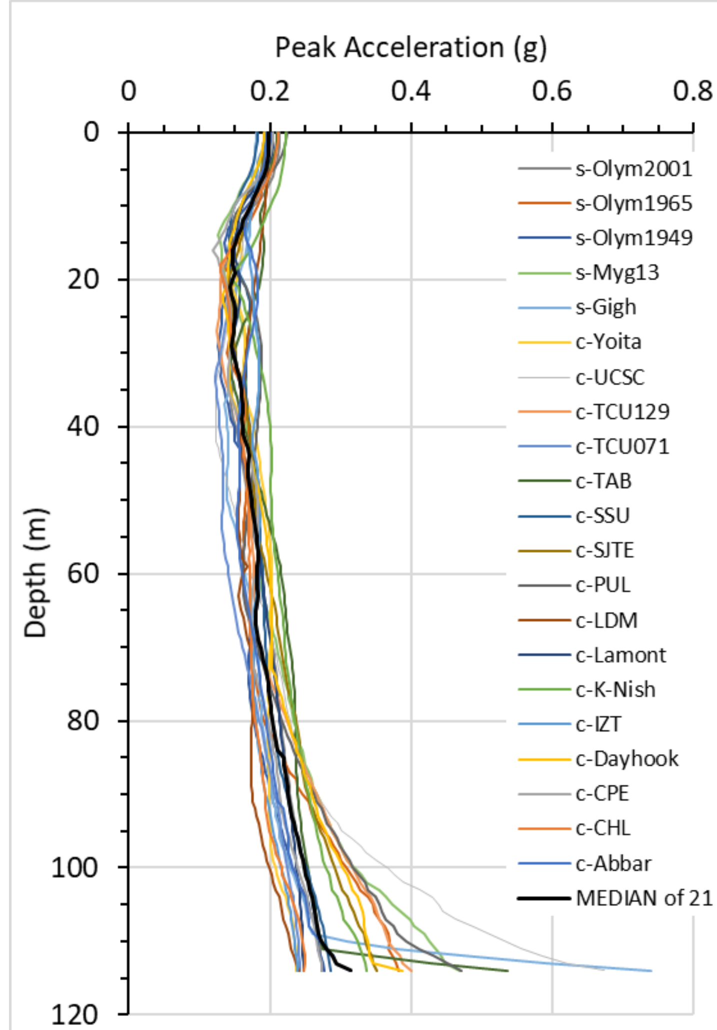
v_I = velocity of incident wave

v_R = velocity of reflection wave

v_b = velocity at the boundary

τ_B = shear stress at boundary





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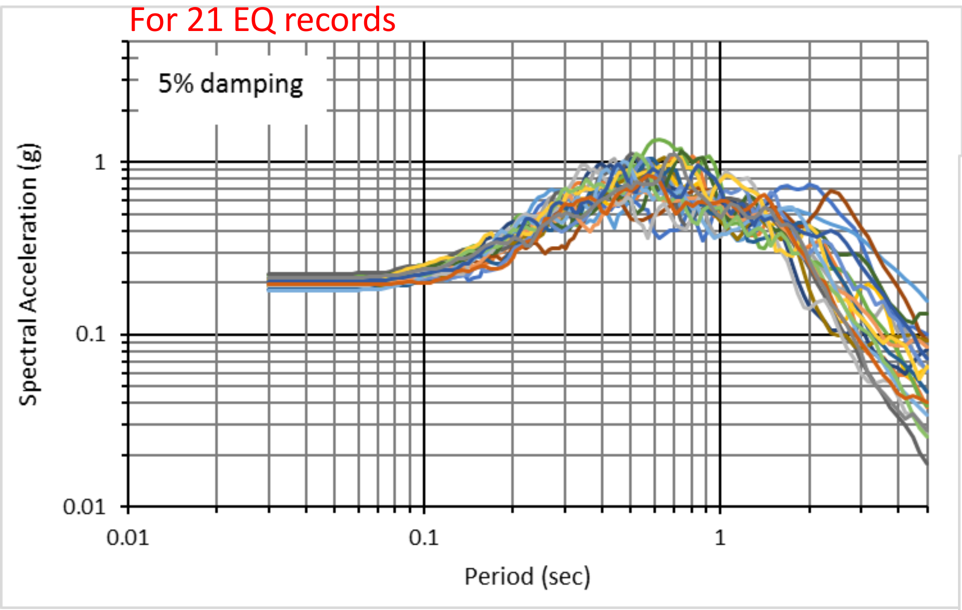
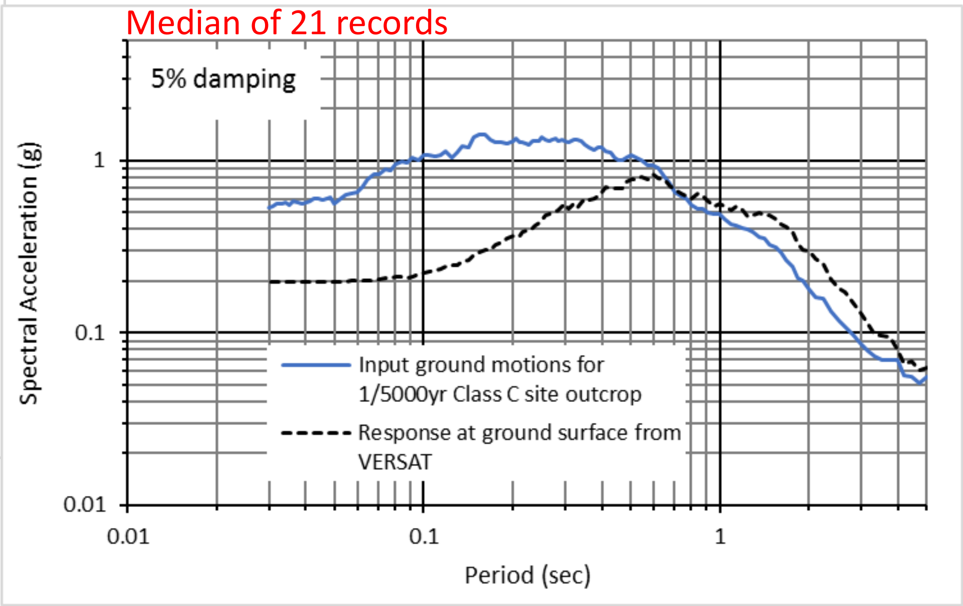
Probability of Liquefaction (P_f), reliability index (β)

Ground surface spectral accelerations from the 21 Records

A large reduction in a_{max} at a site, due to:

- **Firm ground (V_s > 360 m/s) encountered at a great depth, i.e., 114 m for RB Port site**
- **General soft soils with a long period, T_1= 0.62 sec**





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Probability of Liquefaction (P_f), reliability index (β)

Soil depth at 11.5 m	VERSAT $N_{1.60}$=24	Reliability Method	
		Sampling	FORM
Median Fs_{liq} - G	1.42	1.40	0.171 [1]
Mean, μ	1.39	1.48	0.171
S. deviation[1] σ	na	0.5	0.069
Reliability β	na	0.97	1.026
$P_f = \frac{N_f}{N}$	na	0.157	-
$P_f = \Phi(-\beta)$	-	-	0.152

[1] Note:

- Reliability FORM result here is referenced to performance function G = $crr_{15} - csr_{15}$ (G=0 is equivalent to conventional FS_{liq}=1

Case A:

Comparison of results by Methods

- **FS_{liq} Median $_{50th\text{-}\%tile}$ is more representative**
- **At 11.5 m depth, FS_{liq}=1.4**
- **P_f = 0.157 by sampling method $_{3465\text{-}points}$ agreed with P_f = 0.152 by FORM method**

Soil depth at 4.5 m	VERSAT $N_{1.60}$=24	Reliability Method $_{sampling}$
Median Fs_{liq}	1.94	1.92
Mean Fs_{liq}, μ	1.90	2.03
S. deviation[1] σ	na	0.69
Reliability β	na	1.49
$P_f = \frac{N_f}{N}$	na	0.024
$P_f = \Phi(-\beta)$	-	-

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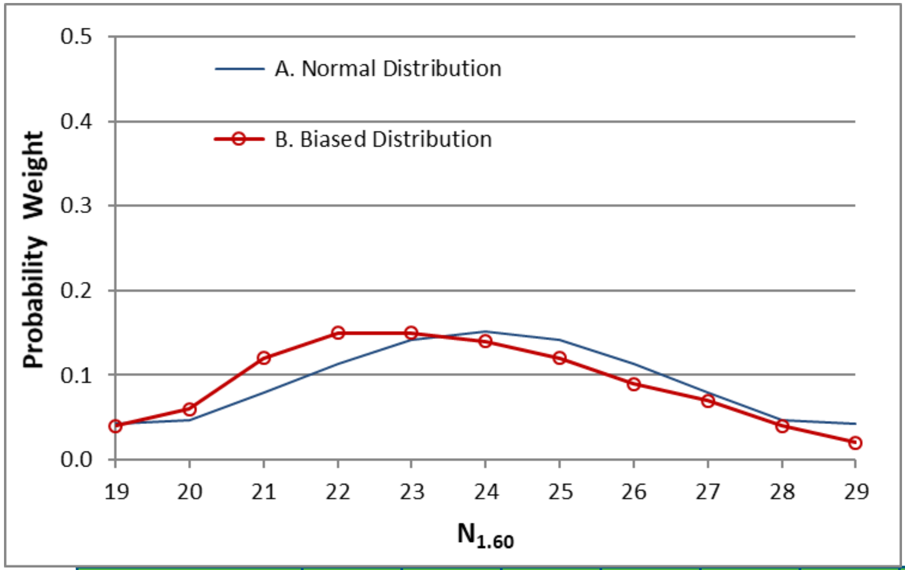
Probability of Liquefaction (P_f), reliability index (β)

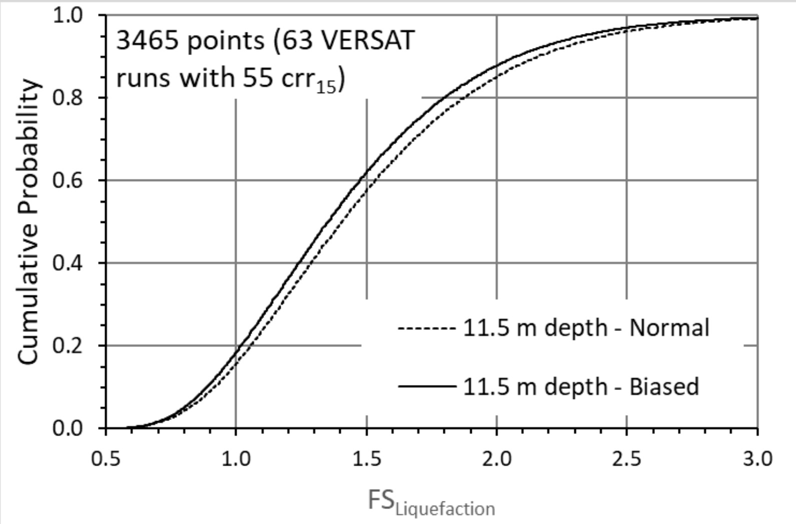


Effect of $N_{1.60}$ data distribution

- **A-set: Normal distribution, CDF = 28% for $N_{1.60} \leq 22$**
- **B-set: Not normal; it has a biased distribution with CDF = 37% for $N_{1.60} \leq 22$**
- **Note: For B-set, $N_{1.60}$ = 22 is often used in a deterministic analysis.**

$N_{1.60}$	19	20	21	22	23	24	25	26	27	28	29	Σ
A. Normal Distribution	0.042	0.047	0.079	0.114	0.142	**0.152**	0.142	0.114	0.079	0.047	0.042	**1.00**
B. Biased Distribution	0.04	0.06	0.12	**0.15**	0.15	0.14	0.12	0.09	0.07	0.04	0.02	**1.00**

Probability of Liquefaction (P_f), reliability index (β)



Comparing results by $N_{1.60}$ between A-set and B-set:

- **There is a pronounced reduction in FS_{liq} from 1.42 to 1.20 by deterministic VERSAT method**
- **$N_{1.60}$ distribution has more impact on high FS_{liq} portion of the fragility curve; thus**
  - **FS_{liq} reduces from 1.40 to 1.35**
  - **P_f increases from 0.157 to 0.184**

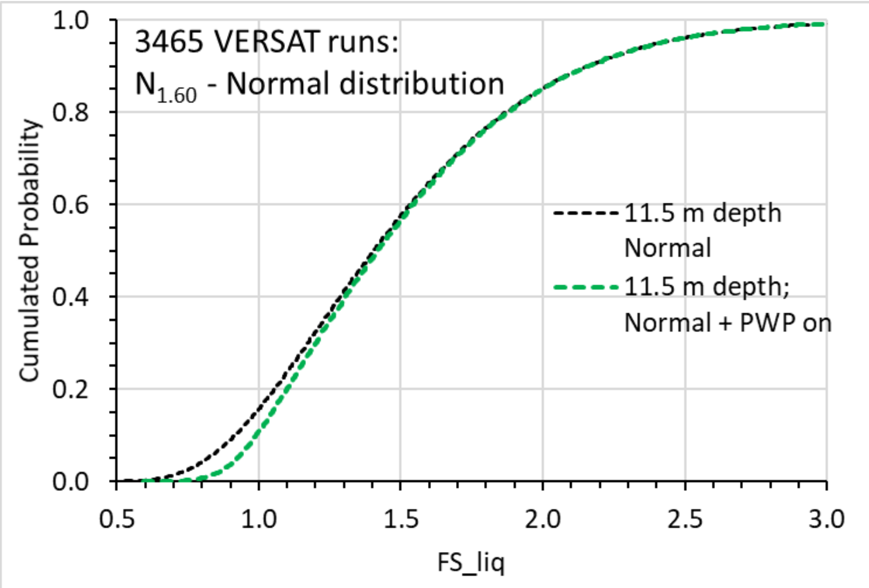
A-set

Soil depth at 11.5 m	VERSAT $N_{1.60}$=24 N1.60 A-set	Reliability Method sampling N1.60 A-set
w. Median Fs_{liq}	1.42	1.40
w. Mean, μ	1.39	1.48
S. deviation[1] σ	na	0.50
Reliability β	na	0.97
$P_f = \frac{N_f}{N}$	na	0.157

B-set

VERSAT $N_{1.60}$=22 N1.60 B-set	Reliability Method sampling N1.60 B-set
1.20	1.35
1.18	1.43
na	0.48
na	0.90
na	0.184

Probability of Liquefaction (P_f), reliability index (β)



Soil depth at 11.5 m	Reliability Method sampling A-set	Reliability Method sampling A-set & PWP-on
w. Median Fs_{liq}	1.40	1.42
S. deviation[1] σ	0.5	0.47
Reliability β	0.97	1.08
$P_f = \frac{N_f}{N}$	0.157	0.108

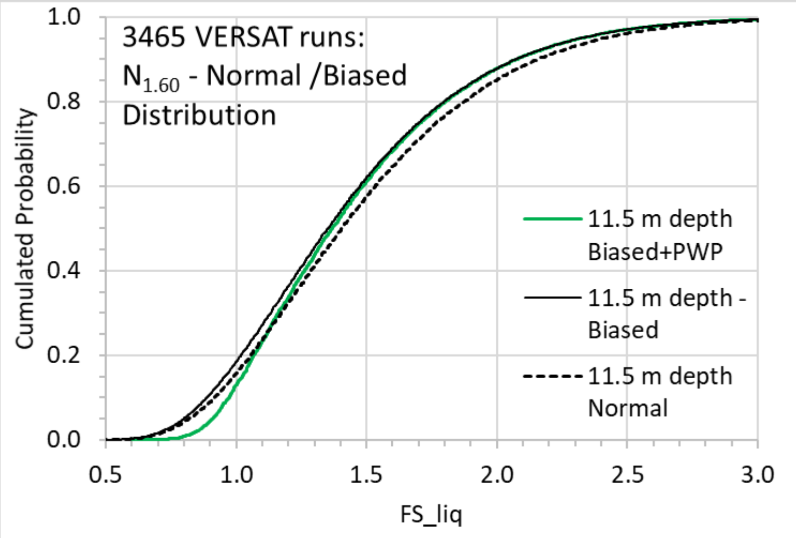
Effective stress analysis including the effect of seismically induced pore water pressures on FS_{liq}:

- **COV ≠ 0 (crr_{15} are affected by csr_{15})**
- **Required 3465 VERSAT dynamic analyses to generate the fragility curve**
- **3465 runs completed in 2 days in a home PC**
- **Results compiled and plotted in 30 min using the Automation processor built in VERSAT**

Effect of PWP on results $N_{1.60}$ A-set

- **Nearly no impact to high FS_{liq} (i.e., high $N_{1.60}$) portion of the fragility curve**
- **Consistent with expectations: more impact at where EQ shear force is near or exceeds the liquefaction resistance, i.e.,**
- **PWP effect has greater impact on probability of liquefaction, less on median FS_{liq}**
- **Effect of PWP has reduced probability of liquefaction P_f to 0.108 from 0.157**

Probability of Liquefaction (P_f), reliability index (β)



Soil depth at 11.5 m	Median FS_{liq}	$P_f = \frac{N_f}{N}$	$N_{1.60}$ Data
Reliability Method $_{sampling}$	1.40	0.157	A-set
+ PWP	1.42	0.108	
Deterministic: $N_{1.60}$ = 24	1.42	-	
Reliability Method $_{sampling}$	1.35	0.184	B-set
+ PWP	1.37	0.130	
Deterministic: $N_{1.60}$ = 22	1.20	-	

Summary results at 11.5 m depth for $N_{1.60}$ B-set :

- **For the more realistic $N_{1.60}$ distribution (in B-set), probability of liquefaction P_f increases to 0.184 from 0.157 for the Norm Distribution (in A-set)**
- **However, effect of PWP has reduced probability of liquefaction P_f from 0.184 to 0.130**
- **Reliability based analysis with PWP indicated $P_f^{5000\text{-yr}}$ =0.130, i.e., annual $P^{\text{Non-Intf.}}_{f\text{-liquefaction}}$ = 2.6 x 10^{-5}**
- **USACE (1999) criterion:**
  - **P_f = 3.0x10^{-5} for good performance**
  - **P_f = 1.0x10^{-3} for above average performance**
- **What is the acceptable annual $P_{f\_liquefaction}$ is a subject for further research !**
- **$P_{f\_liquefaction}$ would be a more accurate (suitable) parameter for measuring the liquefaction potential than the conventional parameter FS_{liq}**

  *** For FS_{Liq} changes from 1.35 to 1.37 (~ 1.5%),**

  P_f reduces much more significantly to 0.130 by 42% !

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Reliability-based dynamic analyses for seismic design optimization in British Columbia

Conclusion Remarks (1)

1. Use of the PSPA approach can reduce the epistemic uncertainties when dealing with seismic hazard including both M9 Interface and M7 non-Interface 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; "human", "belief".

2. In the Lower Mainland: Don't use the UHS (such as Canada seismic hazard values from the NRC website) that include contributions from both the M7 and the M9 earthquake sources.
3. For the design 1/2475-yr ground motions: Derive the source specific spectra, i.e., the 1/5000-yr spectra for subduction Interface EQ (~M9) and the 1/5000-yr spectra for non-Interface EQ (~M7) – using OPENQUAKE
   - Don't only use 1/2475 spectra (Intf. and Non-Intf) for design . They are far less than the required EQ intensity.
4. Conduct analyses using ground motion records for the 1/5000-yr spectra (Intf. and Non-Intf.)
5. Do design using the higher demand from the two sets of results (Intf. Vs. Non-Intf). If necessary, conduct analyses for refinement using 1/2475-yr or 1/10,000-yr spectra (Intf. and Non-Intf.) (Wu 2018)

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Conclusion Remarks (2)

6. Probability-based dynamic analyses (such as soil liquefaction potential assessment) provide a more accurate or representative solution
7. The efforts required for the probability-based analyses are well manageable even for engineering design. The Automation processor built in VERSAT provides the tool.
8. More works are required to
   - Tie the probability of liquefaction ($P_{f\text{-liquefaction}}$) with design requirement and hopefully built into a Design Guideline
   - $P_{f\text{-liquefaction}}$ for Subduction Interface earthquake sources are needed to calculate the total $P_{f\text{-liquefaction}}$ for a site. The work presented in this study is the 1st part of a more comprehensive study
   - $P_{f\text{-liquefaction}}$ at other levels of ground motions are needed to produce a more complete fragility curve

Reliability-based dynamic analyses for seismic design optimization in British Columbia

Information: http://www.wutecgeo.com/versat-2d.aspx

PSPA for 1D liquefaction analysis, and more, OPEN and free for everyone

VERSAT-2D v.2019.10 (new) ***- OPEN standalone version (max. 1500 elements) free for everyone***

Note: Microsoft .Net Framework 2.0 or higher would meet the operation system (OS) requirements to run VERSAT-2D; Otherwise, your computer OS needs to install them, Download Microsoft .NET Framework Version 3.5 Now

- Free download VERSAT-2D_OPEN_2019.10 - click
- This version is capable of conducting probabilistic seismic performance analysis (PSPA).

Questions ?