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Input Ground Motions for Performance-based Design of Soil-structure Systems

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ABSTRACT

Input ground motions play a key role in the design and analysis of soil-structure systems under seismic loading. Seismic loading-induced soil displacements constitute a key input for assessing the performance of structures supported on soils that exhibit non-linear behavior and/or a significant reduction in stiffness and strength such as due to liquefaction. For structures supported on competent soils, their response may be controlled by the inertial demand rather than the soil displacement demand. The selection of input ground motions needs to account for the mechanisms expected to govern the design, i. e. inertial loads or displacements. Due to the unique plate tectonic set up that exists offshore of Vancouver Island, seismic design in Southwestern British Columbia considers ground motions originating from three sources of earthquakes; i.e. shallow crustal, deep Inslab and interface. The distribution of input ground motions that represent each earthquake source generally follow the percent contributions from the different earthquake sources via de-aggregation of the inertial hazard at a site. While this approach may be appropriate for soil-structure systems controlled by the inertial demand, different time-history distributions may be more appropriate for soil-structure systems designed using performance-based or displacement-based methods. The development of ground motion records is an interactive process amongst consultants carrying out the seismic hazard assessment and the end-user designer. The paper discusses an end-user's perspective of the state-of-practice of development of input seismic ground motion time-series for design of soil-structure systems. Key aspects such as the depth of application of ground time-series, response quantities of interest and associated design philosophies, key inputs and assumptions made in the development of various Ground Motion Models (GMMs) that the end-users are generally unaware of are discussed.

Keywords: Ground motions, performance-based design, soil-structure, interaction.

INTRODUCTION

Soils are inherently non-linear and inelastic. They exhibit stress-level and stress path dependent behavior. Unlike some of the engineering materials like steel and concrete, soils undergo both shear strains and volumetric strains when subjected to cyclic shear stresses induced by earthquake shaking. The intensity and duration of shaking have a significant impact on soil behavior and hence the seismic behavior of soil-structure systems.

Soils exhibit a wide range of load-deformation or stress-strain behavior when subjected to seismic shaking – varying from cyclic mobility that involves gradual softening of the material with the application of each cycle of loading to cyclic liquefaction that involves rapid build-up of excess pore water pressures and a rapid collapse of the soil structure. The former phenomenon results in smaller and controlled lateral displacements whereas the latter results in large lateral displacements associated with flow of soil as a frictional fluid.

Most soils require a few cycles of strong shaking to initiate the structure alterations and the resulting softening. Prior to softening, soils are capable of transmitting moderate to strong shaking associated with the upward propagation of seismic waves. With the onset of softening, the ability to transmit strong shaking subsides and displacements and/or strains start to accumulate. The timing of this transition is difficult to predict and depends on the in-situ relative density of soil, intensity of ground shaking, soil type and soil stratigraphy. For this reason, soil-structure systems need to be designed for both inertial and displacement demands in order to meet the seismic performance expectations.

While estimating the inertial demand is relatively straight forward, estimating reliable ground displacement demand is complex and involves detailed analyses and requires the following:

1. Information on soil stratigraphy, strength and stiffness of various types of soils;

2. Constitutive models that can simulate the cyclic response of different soil types that constitutes the site soils; and

3. Optimal characterization of input ground motions that represent the seismic sources that contribute to the seismic hazard at the site.

Seismic assessment of soil-structure systems almost always requires numerical simulations/ground response analyses. For this and reasons noted above, performance-based earthquake engineering places a high degree of importance on seismic ground motions used as input.

SEISMIC HAZARD AT A SITE

Seismicity in a given region results from plate tectonic activity. Depending on the plate tectonic set up in the region of interest (i.e. where a project site is located), the seismic hazard may result from one or multiple types of earthquake source types; i.e. shallow crustal earthquakes in eastern Canada versus shallow crustal, deep Inslab and interface subduction earthquakes in southwestern British Columbia, Canada.

Establishing the seismic hazard in sites impacted by a single earthquake type is relatively straightforward. However, establishing the seismic hazard in sites impacted by multiple types of earthquakes is complex and requires special and detailed considerations.

Seismicity in southwestern British Columbia results from the offshore subduction of the Juan de Fuca plate beneath the North American Plate. This unique plate tectonic set up results in three different types of earthquakes each with its own characteristics:

- Shallow crustal earthquakes occurring within the North American Plate: 10-20 km in depth, M6.-7.5 in magnitude.
- Deep Inslab earthquakes occurring within the subducting plate: 60-70 km in depth, up to M7.5 in magnitude; and
- Interface earthquakes occurring at the interface between the North American and Juan de Fuca Plates: 125+ km offshore of Vancouver, up to M9 in magnitude.

Structural engineers rely on the design Uniform Hazard Response Spectrum (UHRS) to estimate the inertial loads imposed on structures. When structures are analyzed using time-series methods, the input ground motion time series are selected to match the UHRS and tectonic characteristics of the region. Response Spectra, however, do not explicitly account for duration of shaking, sequences and directionality of seismic shaking pulses.

For a site impacted by a single type of earthquake, the UHRS has contributions from only one type of earthquake. However, for sites impacted by multiple types of earthquakes, the UHRS has contributions from all types of earthquakes. For a given return period, the proportions of contribution from each type of earthquake vary with period. As an example, for a site in Vancouver and for the 2475-yr demand, the short period spectral accelerations are dominated by crustal earthquakes whereas the long period spectral accelerations are dominated by subduction interface earthquakes.

No single earthquake can represent the shaking intensities at all periods represented by the design UHRS. For this reason, Conditional Mean Spectra are often considered for design. Conditioning periods ranging from 0.1 to 0.2 seconds are often considered to represent short period crustal and Inslab earthquakes, whereas conditioning periods ranging from 1 to 2 seconds are often considered to represent interface earthquakes. Overall, the UHRS established for a given site/location is considered to be the envelope of the seismic hazard applicable for the site/location.

KEY FEATURES OF GROUND MOTION TIME-SERIES

Recorded ground motion time-series from past earthquakes vary considerably with earthquake magnitude, distance to rupture, and ground conditions characterized based on Vs30. In general, smaller magnitude earthquakes result in ground motions with shorter durations, earthquakes with a closer rupture distance result in stronger ground shaking and stronger ground conditions result in lower intensity of shaking. Seismologists use the following additional ground motion characteristics during selection of time-series for seismic analysis:

a. Peak intensity of shaking depicted by variables such as Peak Ground Acceleration (Amax) and Peak Ground Velocity (Vmax)

b. Arias Intensity (AI)

c. Cumulative Absolute Velocity (CAV)

d. Duration of Shaking measured in terms of bracketed duration, cumulative duration, significant duration (D5-75 and D5-95) or CAV5 with each duration measure defined differently, and

e. Spectral Shape of the recorded ground motions and/or Vs30

As noted previously in Introduction above, duration of strong ground shaking has a significant impact on the seismic displacements of soil-structure systems due to the degradation of soil structure and softening associated with the development of excess pore water pressures. However, duration prediction models are not well-established. The available duration prediction models are empirical and most of them have been developed for crustal earthquakes. In 2018, a data base of subduction earthquakes was developed (i.e. NGA-Subduction DB). Establishing reliable shaking durations for subduction interface earthquakes is still, however, being carried out on a project specific basis.

DEPTH OF APPLICATION OF GROUND MOTION TIME-SERIES

Response spectra and corresponding ground motion time-series are often developed for a reference ground condition established based on Vs30. Vs30, however, is not a true reflection of the Vs profile for a given site. Vs30 is an index associated with the Vs profile.

The Ground Motion Models (GMMs) developed based on broader regional data used in the probabilistic seismic hazard calculations have their own inferred Vs profiles. There is limited literature summarizing the Vs profiles used in the GMMs. If the Vs profile of the site differs significantly from the Vs profiles assumed in the GMMs, there could be over or under-prediction of site amplifications.

The current S-O-P is to apply the ground motion time-series at a depth where the Vs profile of the site reaches the reference Vs30. By shifting the Vs profiles used in the GMMs to match the gradient and magnitude of the site Vs profile, the resulting effects of over or under-predictions in site amplification can be minimized (ref. Williams and Abrahamson, 2021). There will still be some in-built amplification effects. Alternatively, one could deconvolve the ground motion time-series using the Vs profiles used in the GMMs and then re-analyze the site response with the site-specific Vs profile as suggested by Al-Atik & Abrahamson (2022).

SEISMIC DISPLACEMENTS FOR PERFORMANCE-BASED DESIGN

There are several approaches available to develop seismic displacements when using the performance-based method in seismic design of soil-structure systems. These are briefly described below.

The most conservative approach is to design for the envelope of computed displacements from all different earthquake types and the corresponding ground motion time-series.

Alternatively, the design could be based on the weighted average displacements established via de-aggregation of the seismic hazard at the conditioning periods of the CMS relative to the earthquake type; i.e. 0.2 second or 1.0 second periods.

The current S-O-P that has been adopted for key infrastructure projects in British Columbia has been to evaluate the mean displacement demands from each earthquake type and for short and long period ground motions separately and designing for the worst-case mean displacements.

When one earthquake type dominates the seismic response of concern, design seismic displacements can be established using ground motion time-series that correspond to that earthquake type/source as proposed by Williams et al (2021). This would entail reanalysis of the soil-structure system with new input ground motion time-series that can be time consuming.

SUMMARY

The attached Appendix illustrates each of the topics described above with examples and graphics where appropriate. Key takeaways for each topic and applicable references are also provided.

The author has prepared this paper as narrative of the Keynote Lecture No. 4 presented in the CCEE-PCEE. While the contents are substantially the same, there may be slight changes in the contents from what were presented on June 28, 2023.

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INPUT GROUND MOTIONS FOR PERFORMANCE-BASED DESIGN OF SOIL-STRUCTURE SYSTEMS

Key Note Address # 4

Dr. Upul Atukorala, PEng

June 28, 2023

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Outline

1. Introduction
2. Seismic Hazard [Topic 1]
3. Key Features of Ground Motion Time-Series [Topic 2]
4. Depth of Application of Input Ground Motions [Topic 3]
5. Design Seismic Displacements for Performance Based Design, PBD [Topic 4]

Acknowledgements

References

Introduction

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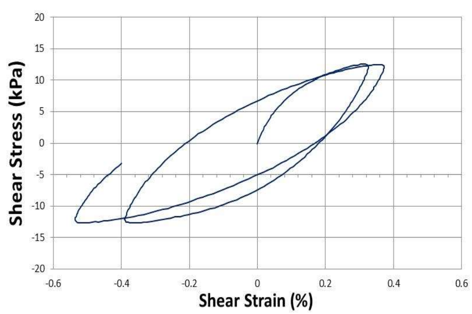
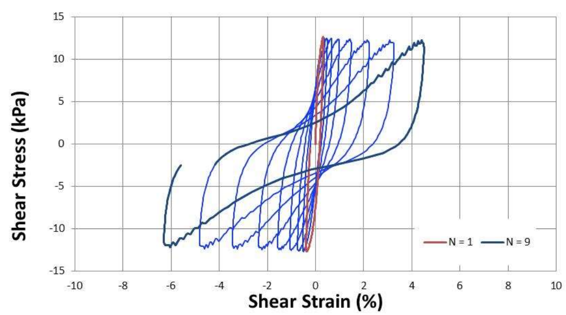
Introduction

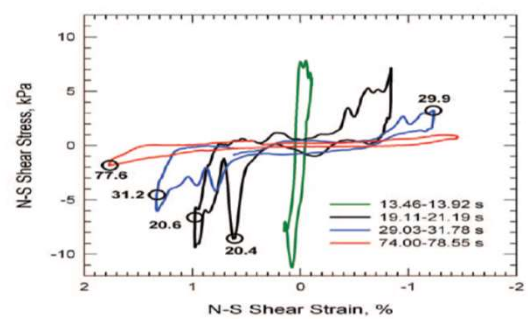
- ❖Soils are inherently non-linear, inelastic, stress level/path dependent and undergo shear strains and volume change when subjected to cyclic loading.
- ❖The intensity and duration of shaking of ground motions have a significant impact on soil behavior and hence the seismic performance of soil-structure systems.
- ❖Soils exhibit a wide range of load-deformation responses when subjected to shaking – ranging from cyclic mobility to cyclic liquefaction. These phenomena result in large lateral and vertical displacements that can compromise the seismic performance expectations of a soil-structure system.



Non-Linear Response



Cyclic Mobility



Cyclic Liquefaction

Introduction, Contd.

- ❖ Few cycles of strong shaking are required to initiate soil softening. Prior to softening, soil can transmit strong shaking. During and after softening, the inertial forces subside and displacements start to accumulate. The timing of this transition is difficult to predict; depends on the level of shaking, soil density, soil type, stratigraphy etc.
- ❖ Need to design soil-structure systems for both inertial and displacement demands to meet the seismic performance expectations.

Estimating inertial demands is relatively straight forward. Estimating <u>reliable displacement demands</u> involves detailed analyses and requires:

- ➢ Information on soil stratigraphy, strength and stiffness,
- ➢ Constitutive models that can simulate seismic response of different soil types, and
- ➢ **Optimal characterization of Input ground motions that represent the seismic sources that contribute to the hazard at the site.**

- ❖ Seismic assessment of soil-structure systems almost always involve numerical simulations/ground response analyses.

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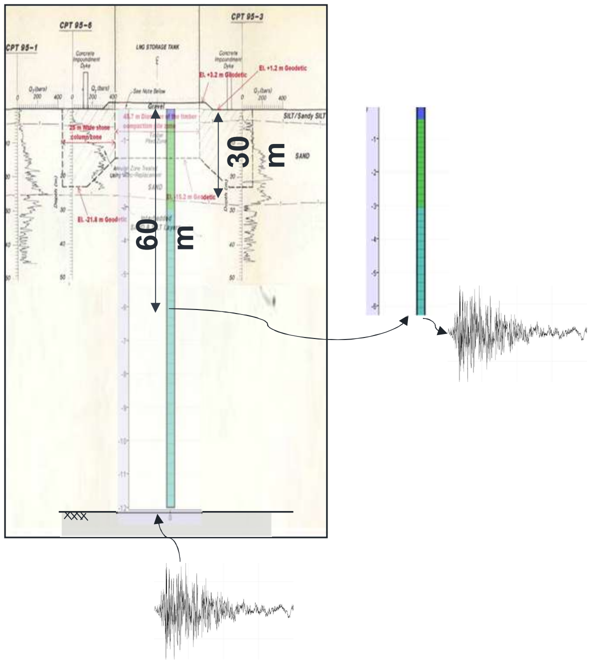
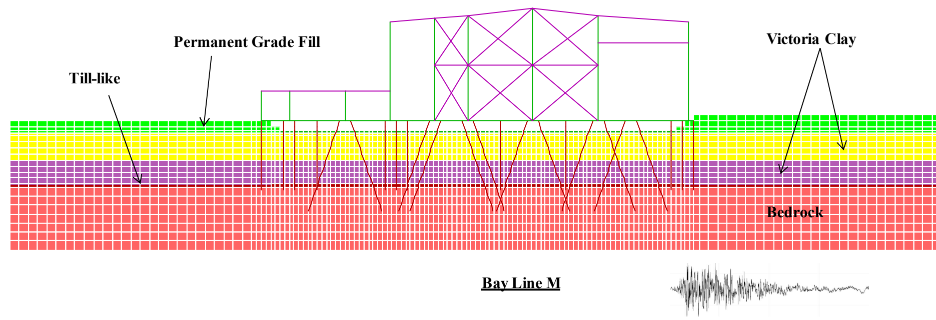
Introduction, Contd.





Performance-based earthquake engineering places a high-level of importance on seismic ground motions used as input.

Topic 1: Seismic Hazard

- ❖ Seismicity in a given region results from plate tectonic activity. Depending on the plate tectonic set up in the region of interest, sites are impacted by multiple types of earthquakes; i.e. shallow crustal, deep Inslab, interface etc., each with its own characteristics.
- ❖ Establishing seismic hazard for sites impacted by a single type of earthquakes is relatively straightforward.
- ❖ Establishing seismic hazard for sites impacted by multiple types of earthquakes, such as in Vancouver, is complex and requires detailed analyses.

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Topic 1

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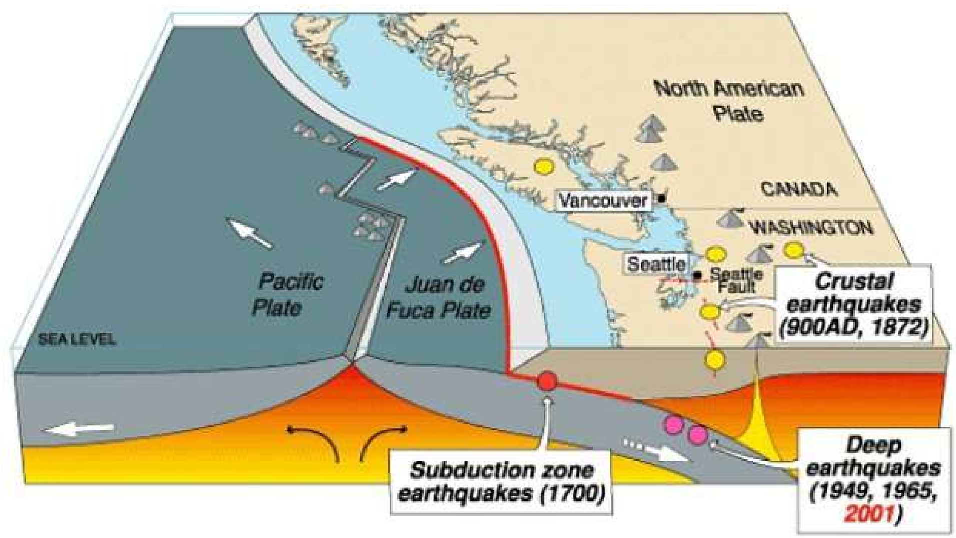
Topic 1: Seismic Hazard, Contd.

❖Seismicity in southwestern British Columbia, Canada results from the offshore subducting of the Juan de Fuca Plate beneath the North American Plate. This unique plate tectonic environment results in three different earthquake types for this region, each with its own characteristics :

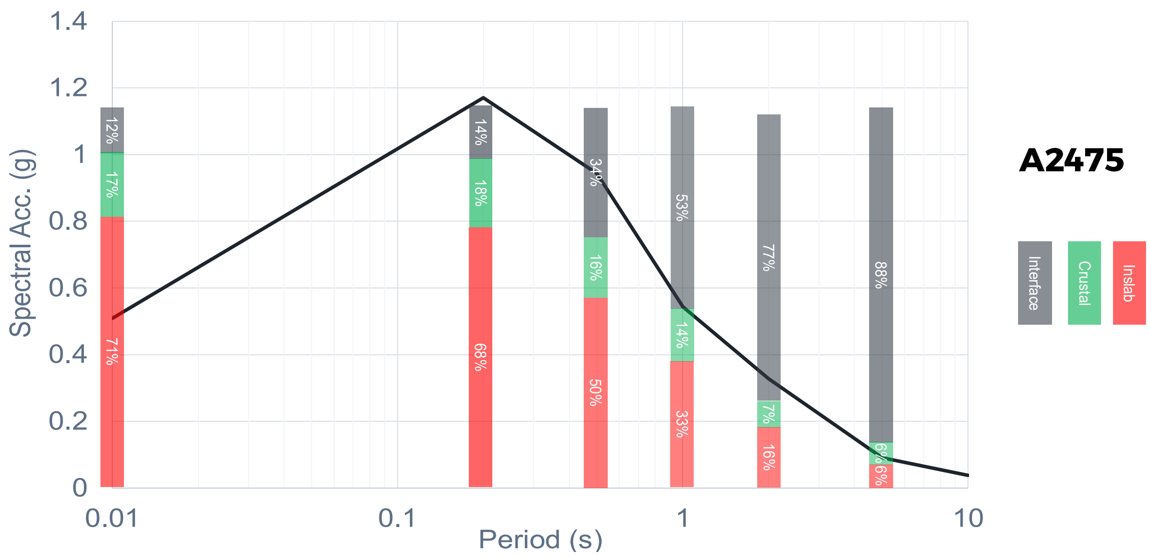
- Shallow crustal earthquakes [North American Plate, 10-20 km depth, M6-7.5]
- Deep inslab earthquakes [subducting Juan de Fuca Plate, 60-70 km depth, upto M7.5], and
- Interface subduction earthquakes [Interface of the North American and Juan de Fuca Plates, Up to M9, 125+ km offshore]



Topic 1

Topic 1: Seismic Hazard, Contd.

- Structural engineering analyses rely on a design response spectrum often referred to as the Uniform Hazard Response Spectrum (UHRS) and associated ground motion time-series.
- For sites impacted by a single type of earthquake, the UHRS has contributions from only one type of EQ.
- For sites impacted by different types of EQs, the UHRS has contributions from a number of different types of EQs. For such sites, long period ground motions have a relatively higher contribution from Subduction Interface EQs compared to short period ground motions.



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Topic 1

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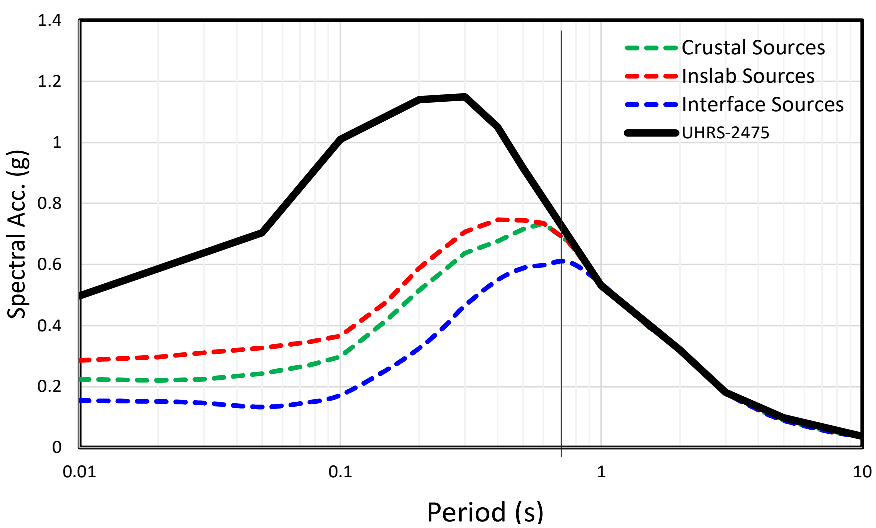
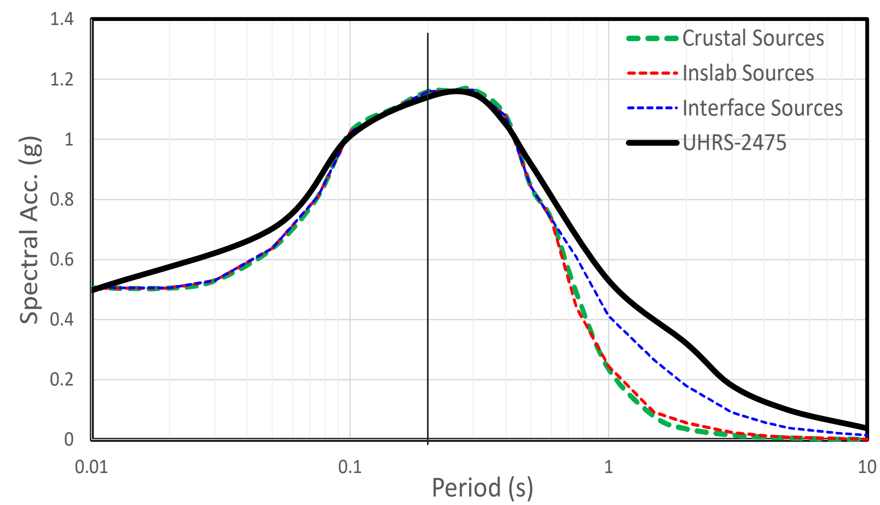
Topic 1: Seismic Hazard, Contd.

❖For sites impacted by multiple earthquake types:

- Develop Conditional Mean Spectra (CMS) to represent Shallow Crustal, Deep Inslab and Interface earthquakes, with the UHRS as the envelope hazard.
- Typically, two conditioning periods ranging from 0.2 seconds representing short period ground motions and 1.0 to 2.0 seconds representing long-period ground motions are used.
- No single earthquake can represent the shaking intensities at all periods represented by the UHRS. Conditional Mean Spectra better represent spectra from past EQs. earthquakes.

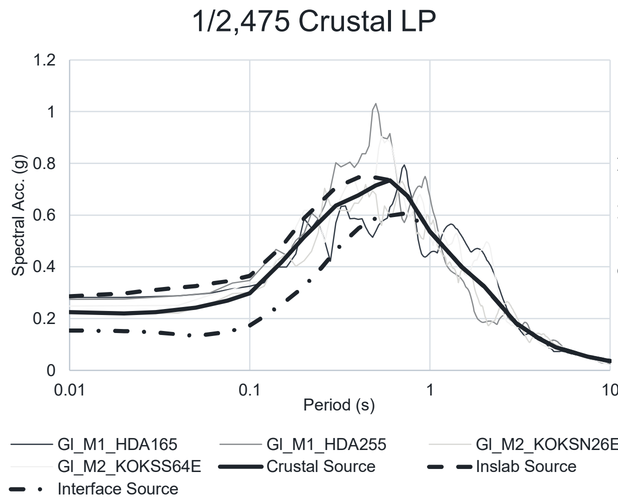


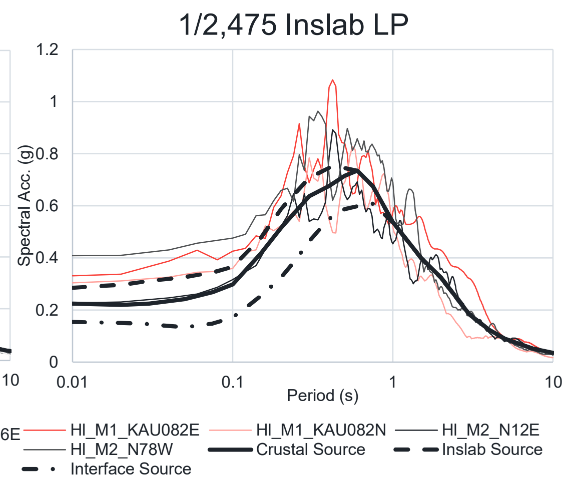


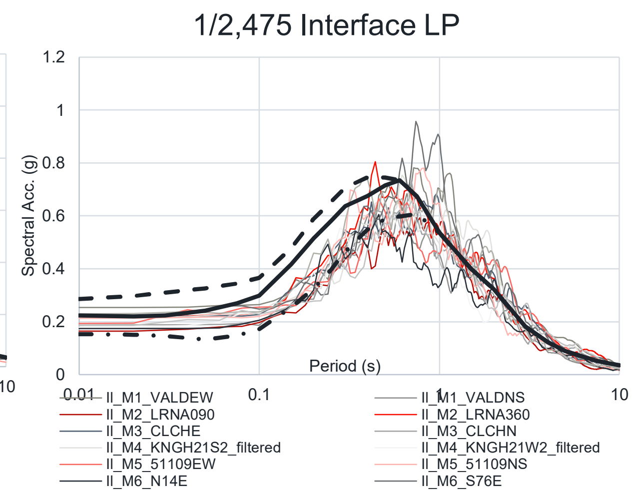
Topic 1

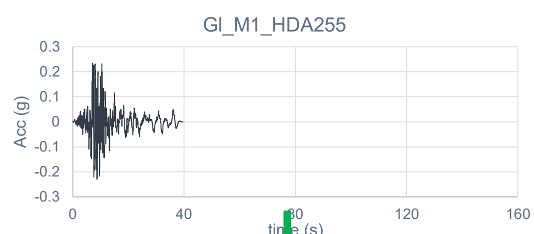
Topic 1: Seismic Hazard, Contd.

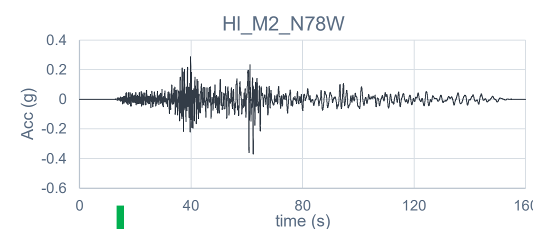
Long Period Conditional Mean Spectra & Ground Motion Time-Series

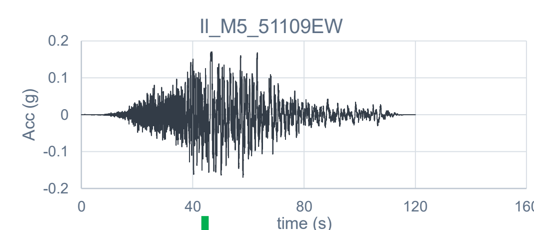












EQ Source	Crustal _LP	Crustal _LP	Crustal _LP	Crustal _LP	Inslab _LP	Inslab _LP	Inslab _LP	Inslab _LP	Interface_ LP	Interface_ LP	Interface_ LP	Interface_ LP	Interface_ LP	Interface_ LP	Interface_LP	Interface_LP	Interface_ LP	Interface_ LP	Interface_ LP	Interface_ LP	Interface_ LP	Interface_ LP
Short name	GI_M1_H DA165	GI_M1_H DA255	GI_M2_K OKSN26E	GI_M2_K OKSS64E	HI_M1_KA U082E	HI_M1_KA U082N	HI_M2_N1 2E	HI_M2_N7 8W	II_M1_VA LDEW	II_M1_VA LDNS	II_M2_LR NA090	II_M2_LR NA360	II_M3_CLC HE	II_M3_CLC HN	II_M4_KNGH 21S2_filtered	II_M4_KNGH 21W2_filtere d	II_M5_511 09EW	II_M5_511 09NS	II_M6_N1 4E	II_M6_S76 E	II_M7_515 62EW	II_M7_515 62NS
Max Acceleration (g)	0.28	0.27	0.22	0.25	0.33	0.30	0.23	0.41	0.25	0.17	0.16	0.22	0.22	0.19	0.22	0.18	0.19	0.21	0.17	0.22	0.23	0.19
Max Velocity (cm/sec)	54.12	51.60	48.76	41.46	81.01	41.14	37.65	52.92	54.72	30.25	35.86	53.96	55.03	42.71	48.41	34.71	73.42	49.21	33.47	67.13	43.14	57.88
Max Displacement (cm)	29.23	20.48	30.68	19.82	41.14	20.63	30.42	17.38	32.90	18.36	22.95	30.50	27.54	26.33	20.35	25.12	32.30	29.18	20.77	33.80	22.45	38.01
Significant Duration $D_{5\text{-}95}$ (se	**13.80**	**19.12**	**37.19**	**36.54**	**15.87**	**22.73**	**88.36**	**80.48**	**26.40**	**29.33**	**41.67**	**37.62**	**38.34**	**44.89**	**69.39**	**68.22**	**39.13**	**47.31**	**42.21**	**39.81**	**35.36**	**42.27**
Significant Duration 5-75 (se	**4.08**	**4.31**	**20.96**	**20.94**	**9.09**	**11.20**	**45.89**	**33.03**	**19.59**	**20.86**	**25.56**	**23.64**	**26.51**	**24.12**	**51.84**	**47.28**	**25.10**	**24.33**	**27.00**	**23.11**	**17.80**	**22.03**
Damage Index((g)^c)	0.78	1.16	2.04	2.22	3.21	2.50	2.72	3.43	1.60	1.07	2.25	2.95	2.30	1.78	2.56	2.44	2.46	2.72	2.77	3.16	2.78	2.20

Topic 1

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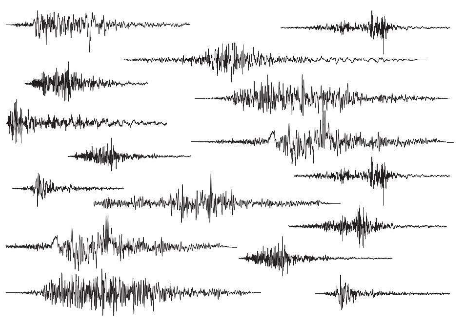
KEY TAKEAWAYS – TOPIC 1

1. Seismic hazard assessment for sites/regions impacted by only one EQ type is relatively straightforward.
2. Seismic hazard assessment for sites/regions impacted by multiple EQ types is complex and involves detailed analyses. One such example is Southwestern BC (SWBC) region of Canada where the seismicity results from the unique tectonic plate set up that exists offshore. Hazard could come from any one of the three different types of earthquakes each with its own characteristics.
3. For SWBC, UHRS has contributions from all three types of earthquakes. Contributions vary with period.
4. UHRS is a design spectrum and does not correspond to any one type of earthquake.
   ➔ CMS or scenario-based response spectra for the different earthquake types based on de-aggregation of seismic hazard.
5. The ground motion time-series selected for design/analysis should reflect key characteristics of earthquakes anticipated at the site.

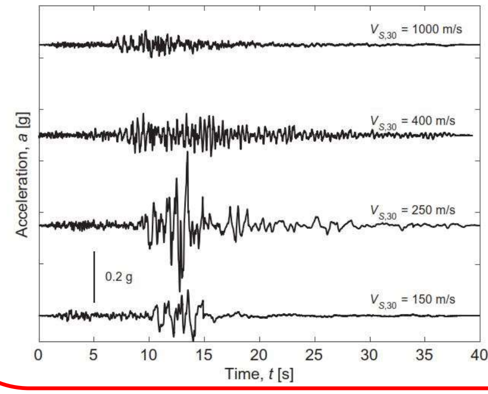
Topic 2: Key Features of Ground Motion Time-Series

Examples Illustrating Complexity (adapted from Baker et al, 2021)

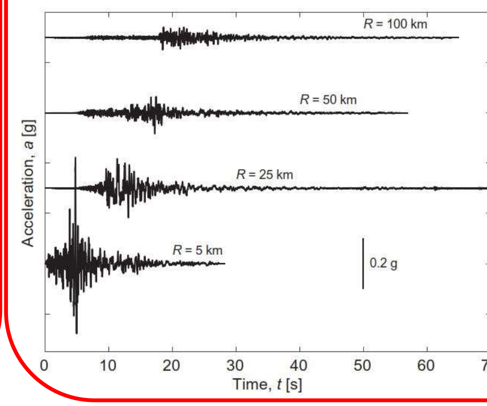
A. Typical Variations



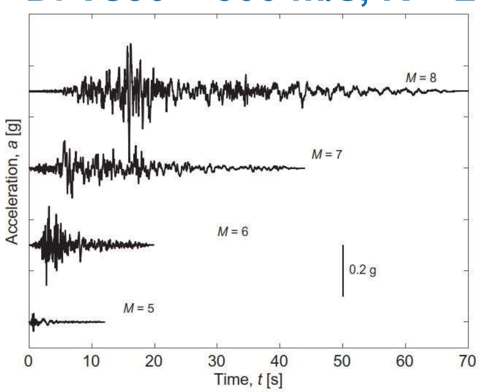
B. M6.9, R=75 km, Varying Vs30



C. M6.2, Vs30 = 500 m/s, Varying R



D. Vs30 = 500 m/s, R = 20 km, Varying M



There are trends:

- **Smaller EQs → shorter in duration.**
- **Closer EQs → stronger shaking**
- **Stronger Ground → lower shaking**

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Topic 2

Topic 2: Key Features of Ground Motion Time-Series, Contd.

Accelerogram	GI_Motion1_RSN778_LOMAP_HDA165	**HI_Motion1_RSN7006533_KAU082E**	II_Motion1_RSN6001826_VALDEW
EQ Source	Crustal _LP	Inslab _LP	Interface_LP
Max Acceleration (g)	0.28	**0.33**	0.25
Max Velocity (cm/sec)	54.12	**81.01**	54.72
Max Displacement (cm)	29.23	**41.14**	32.90
Vmax/Amax (sec)	0.20	**0.25**	0.22
Acceleration RMS (g)	0.05	**0.05**	0.05
Velocity RMS (cm/sec)	12.43	**9.88**	11.38
Displacement RMS (cm)	9.26	**7.35**	8.80
Arias Intensity (m/sec)	**1.27**	**2.92**	**2.47**
Characteristic Intensity	0.06	**0.09**	0.08
Specific Energy Density (cm2/sec)	6132.21	**8781.41**	10226.32
Cum. Abs. Velocity (cm/sec)	**1012.39**	**1855.28**	**2097.39**
Acc Spectrum Intensity (g*sec)	0.21	**0.30**	0.19
Vel Spectrum Intensity (cm)	231.47	**242.44**	233.29
Housner Intensity (cm)	224.17	**237.07**	217.88
Sustained Max.Acceleration (g)	0.22	**0.25**	0.20
Sustained Max.Velocity (cm/sec)	46.17	**44.57**	39.56
Effective Design Acceleration (g)	0.28	**0.31**	0.26
A95 parameter (g)	0.28	**0.32**	0.25
Predominant Period (sec)	0.30	**0.18**	0.30
Significant Duration D_{5-95} (sec)	**13.80**	**15.87**	**26.40**
Max Incremental Velocity (cm/sec)	104.57	**72.30**	73.82
Damage Index((g)^c)	0.78	**3.21**	1.60
Number of Effective Cycles	3.47	**6.73**	4.24
IP Index	18.76	**23.16**	38.43
Sa,avg (g)	0.48	**0.53**	0.46

Additional Characteristics Considered During Selection of Time-Series for Seismic Analysis

1. Peak Intensity of Shaking; Amax, Vmax
2. Arias Intensity, Ia; $I_a = \frac{\pi}{2g}\int_0^{t_{max}} [a(t)]^2 dt$
3. Cumulative Absolute Velocity, CAV
   $CAV = \int_0^{t_{max}} |a(t)| dt$
4. Duration of Shaking
   e.g. bracketed duration, cumulative duration, significant duration [D_{5-75} or D_{5-95}], CAV5, etc. defined differently.
5. Spectral Shape, and/or V_{s30}

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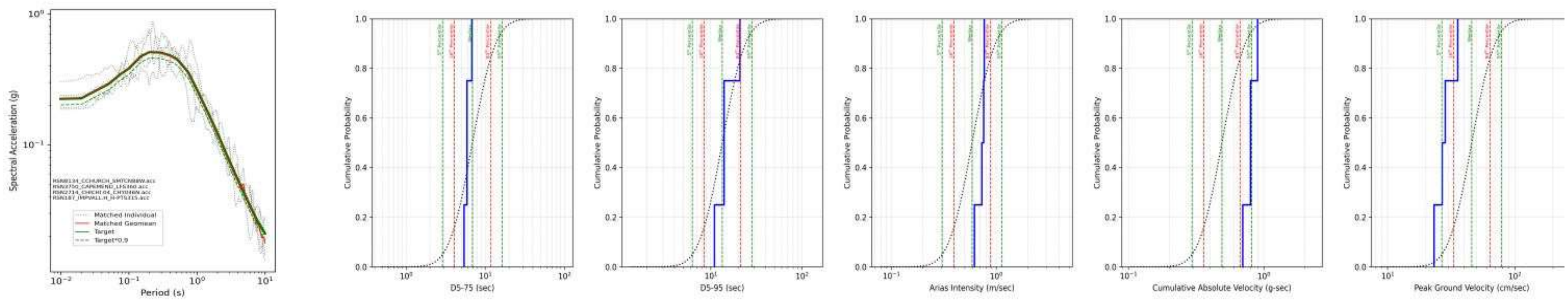
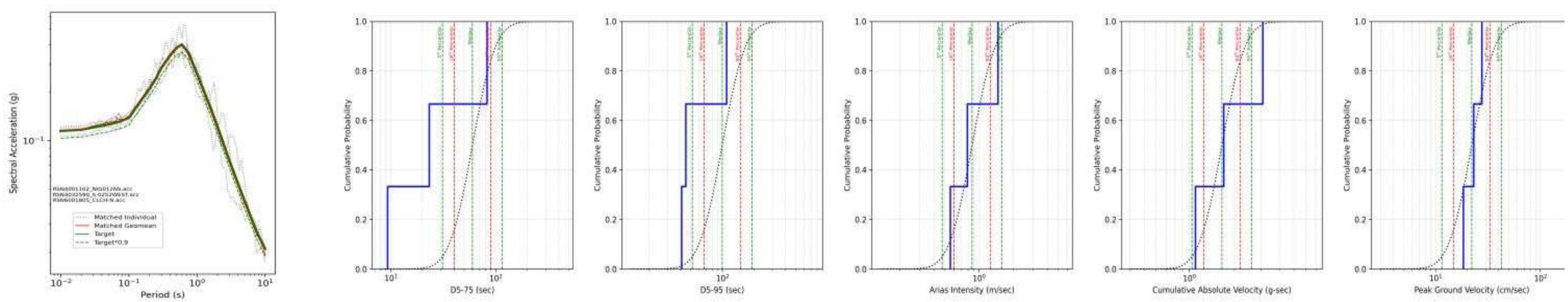
Topic 2

Topic 2: Key Features of Ground Motion Time-Series, Contd.





Topic 2

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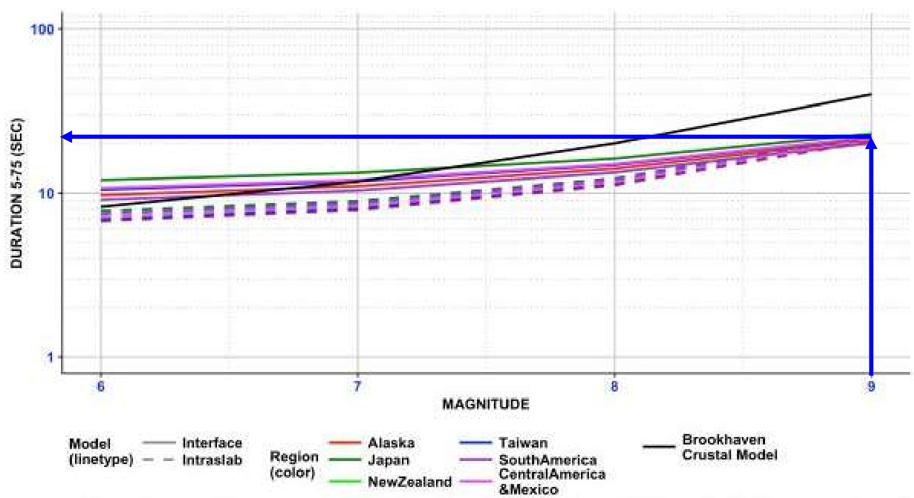
Topic 2: Key Features of Ground Motion Time-Series, Contd.

Duration Prediction Models (DPMs) for are not well-established.

- Available duration prediction models are empirical.
- Most duration prediction models are for crustal EQs
- Recent efforts to better establish duration predictions for subduction EQs ➔ NGA-Subduction Data Base.



Duration model versus earthquake magnitude at R_{jb} = 100 km. Solid lines are interface source-type, dashed lines are intraslab source-type, black line is Brookhaven(crustal model).

[After Walling, Kuehn, Abrahamson, and Mazzoni, 2018]

❖ $D_{5\text{-}75}$ durations established for some recent projects:

- Projects 1 & 2 = 60 sec
- Project 3 = 43 sec
- NGA-Sub Data = 20 sec

Notes:

1. Independent of the return period.
2. For Project 3, based on compilation of a small subset of interface events.
3. Reliable targets for $D_{5\text{-}75}$ duration currently unavailable.
4. Duration will have a significant impact on displacement calculations.

Topic 2

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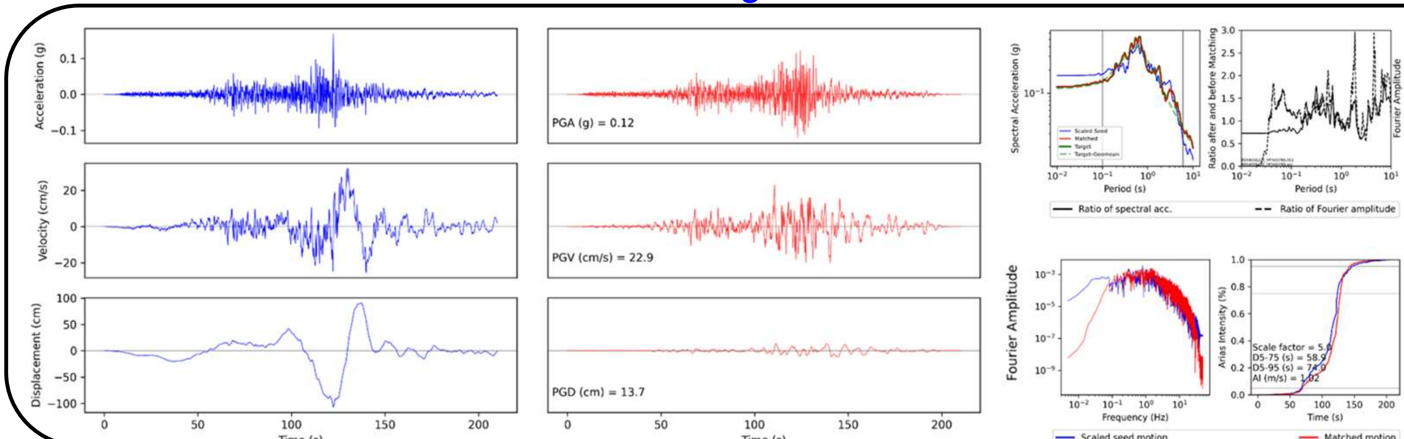
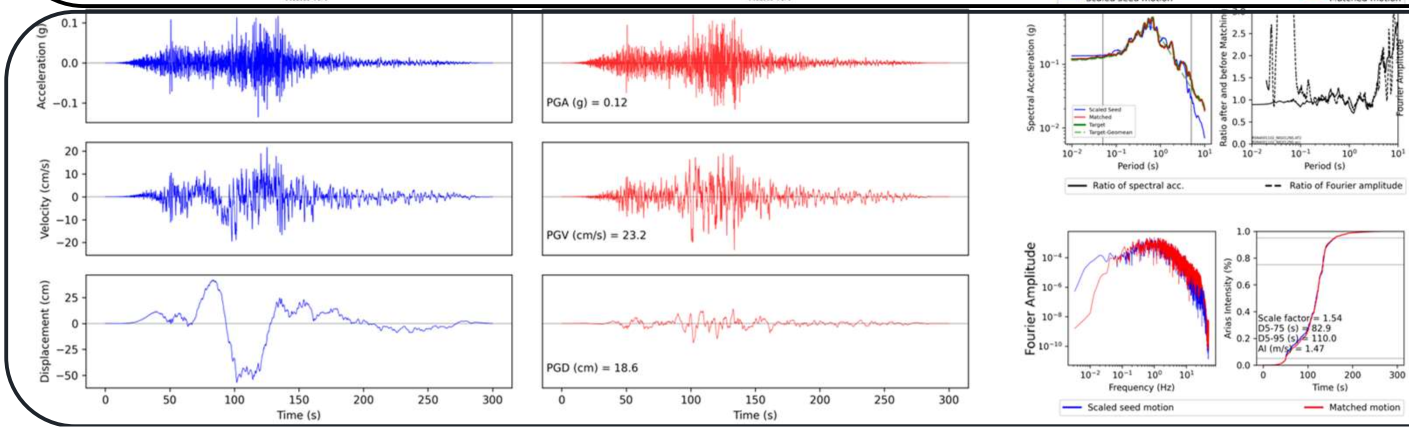
Topic 2: Key Features of Ground Motion Time-Series, Contd.

E. Spectral Shape: measure of frequency content of the time-series

- A measure of the frequency content of the time-series.
- Does not indicate duration of shaking and the sequence of strong pulses.
- Does not indicate direction of shaking.



Tohoku, Japan 2011, NAMBU station [RSN4001228], Vs30 = ~ 400 m/s



Tohoku, Japan 2011, KANOSE station [RSN4001102] Vs30 ~ 230 m/s

Topic 2

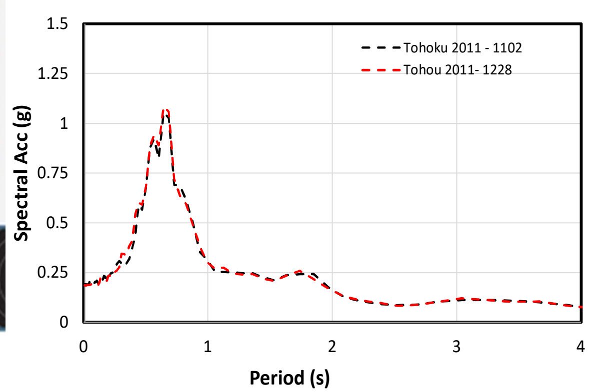
Topic 2: Key Features of Ground Motion Time-Series, Contd.

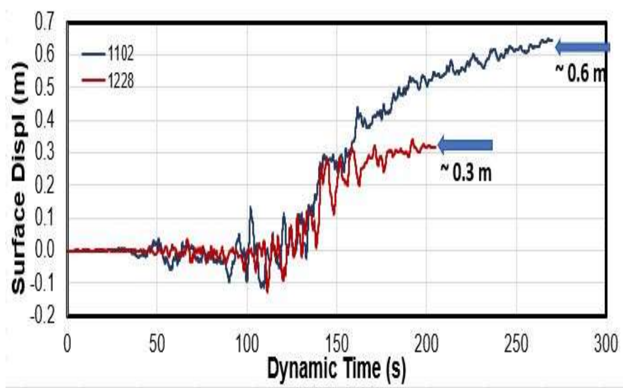
Secondary Variables of the 2 records

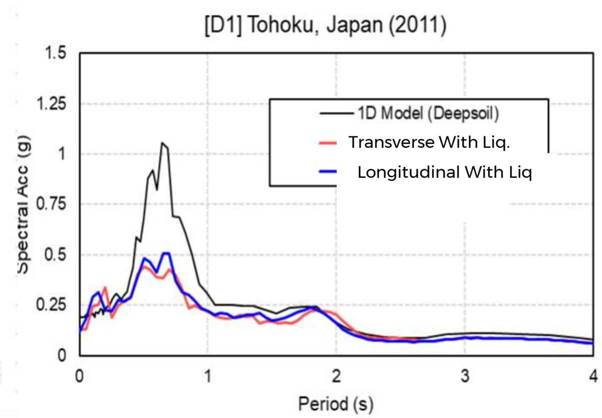
RSN	AEP	File Name	PGA (g)	PGV (cm/s)	AI (m/s)	CAV (g-s)	D_{5-75} (s)	D_{5-95} (s)
4001228	1/2,475	RSN4001228_YMN007NS	0.12	22.9	1.0	2.1	59	74

RSN	AEP	File Name	PGA (g)	PGV (cm/s)	AI (m/s)	CAV (g-s)	D_{5-75} (s)	D_{5-95} (s)
4001102	1/2,475	RSN4001228_YMN007NS	0.12	23.2	1.47	3.1	83	110

- ❖ The Record from Tohoku Kanose Station [RSN4001102] produced displacements that were twice as large as the displacements from Tohoku Nambu Station record [RSN4001228] for the same soil profile, although the spectral shapes were the same.
- ❖ The site analyzed had layers that liquefied.





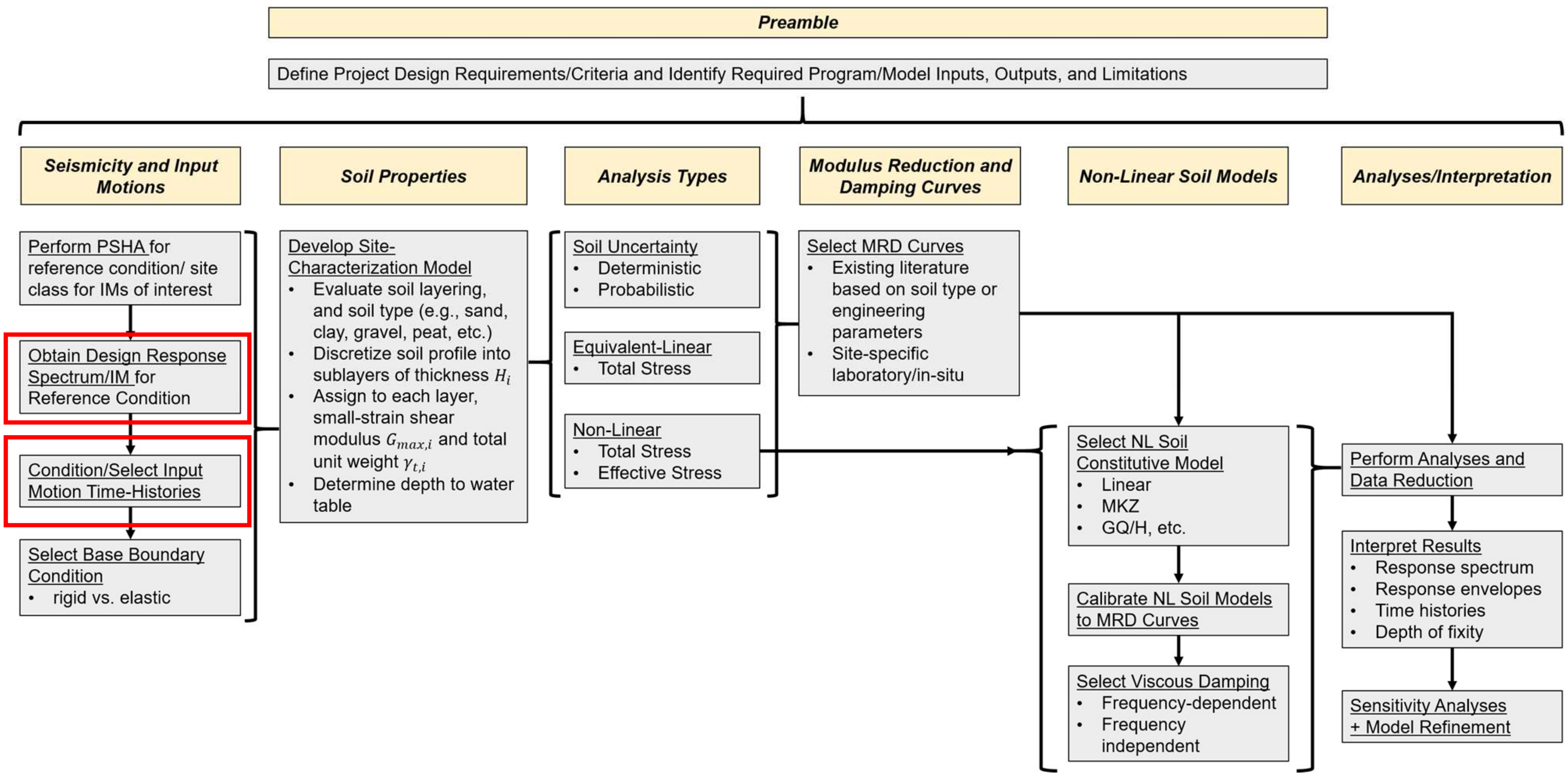


KEY TAKEAWAYS – TOPIC 2

1. Peak intensity measures (IMs), Arias Intensity, Cumulative Absolute Velocity, Duration of Strong Shaking, Spectral Shape and V_{s30} are used when selecting input ground motion time-series for design/analysis.
2. Response spectra do not explicitly account for duration of shaking, sequences and directionality of pulses.
3. Duration is important for geotechnical engineering analysis. Saturated loose to compact cohesionless soils and non-plastic silts soften during ground shaking leading to large permanent displacements.
4. Duration Prediction Models are empirical and not well-established for Subduction Interface ground motions. Target durations need review on a case-by-case basis.

Topic 3: Depth of Application of Ground Motions

A Site Response Analysis involves multiple steps and processes (ref. Recommended SSRA Best Current Practice, 2021):



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Topic 3

Topic 3: Depth of Application of Ground Motions (Contd.)

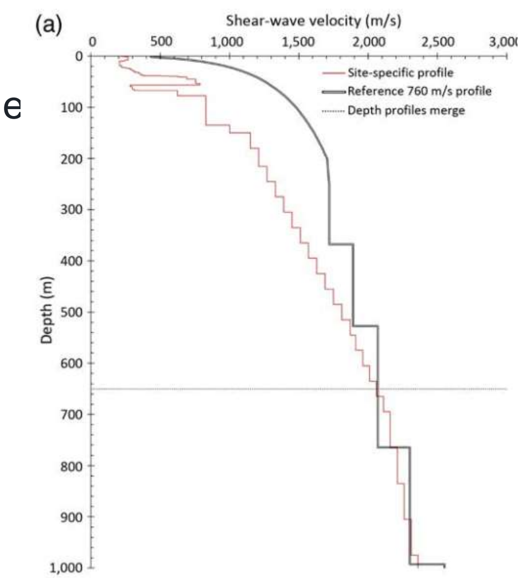
<u>Obtain Design Response Spectrum/IM</u> for Reference Condition

❖ Establish the Design/Target Response Spectrum for a Reference Ground Condition. i.e. time-averaged V_s over the top 30 m of the profile referred to as V_{s30}

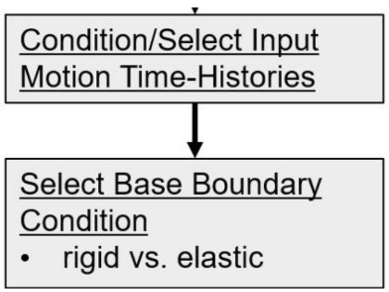
❖ V_{s30} is not a true reflection of the V_s profile for a given site. V_{s30} is an index associated with the V_s profile.

❖ What is not understood is that the GMMs developed based on broader regional data have their own inferred V_s profiles. The V_s profile a given site of interest may be different from the V_s profile applicable for the GMM (ref. Al Atik & Abrahamson, 2022).

  ➢ Could lead to under- or over-estimation of site response



Topic 3: Depth of Application of Ground Motions (Contd.)

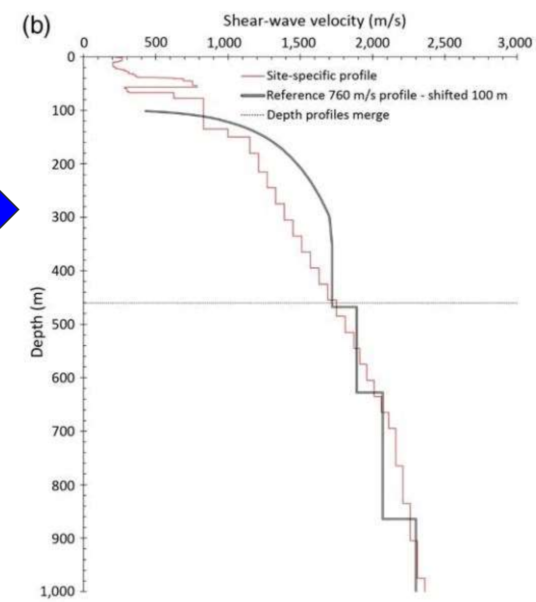


❖ Depth of Application of Ground Motions - Available Approaches:

a) Apply the ground motions at the depth where V_{s30} = V_s => this is the current state-of-practice.

a) Shift the V_s profile used in the GMM in depth to match the gradient and magnitude of the site V_s profile. Apply the ground motions at that depth; e.g. after Williams & Abrahamson, 2021. The method will lead to some in- built amplification/de-amplification effects.

b) Deconvolve motions with GMM Vs profile and reanalyze with site-specific profile [ref. Al Atik & Abrahamson, 2022]



Topic 3

KEY TAKEAWAYS – TOPIC 3

1. V_{s30} is an index associated with a shear wave velocity profile for a site. The V_s profile dictates the site response.
2. Establish Design UHRS or Targe Scenario Spectra for the V_{s30} of the site. Input ground motion time-series are developed for this V_{s30}.
3. Ground Motion Models (GMMs) use their own V_s profiles, which may be different from the V_s profile of the site.
4. The S-O-P is to apply the input ground motions at a depth where $V_{s30} \sim V_s$ (from the profile). This can result in double counting of amplification/de-amplification for a given site.

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Topic 4

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Topic 4: Design Seismic Displacements for Performance-Based Design

- **Approaches to Establish Design Displacements for PBD:**
  a) Design for the envelope of computed displacements from all different earthquake types and ground motions → results in a very conservative design

  b) Establish the weighted average displacements based on de-aggregation of spectral hazard for the conditioning periods of the CMS; e.g. 0.2 sec and 1.0 sec.

  c) Evaluate mean displacements from each EQ source type and short and long period ground motions separately. Design for the worst case mean displacements [Note: This approach requires analyses to be carried out using a sufficient number of ground motion time-series that represent each EQ source type and for short and long period scenarios].
  This approach has been adopted for key infrastructure projects.

  d) Establish ground motion hazard by source type
  Justifiable when one type of earthquake dominates the displacement response. Procedure results in a seismic displacement demand consistent with the hazard [ref. Williams et al, 2021, draft manuscript].

  e) Should we start with target displacement spectra? Currently under development.

Topic 4

KEY TAKEAWAYS – TOPIC 4

1. Evaluate mean displacements from each EQ type for short and long period ground motions separately. Design for the worst case mean displacements. The method accounts for key characteristics of ground motions from different EQ types.
2. The currently followed response spectra-based seismic hazard for regions impacted by multiple EQ types may not be suited for projects where seismic displacements control the design.