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The Effect of Different Strong Ground Motion Scaling Methodologies on Cyclic Stress Ratio (CSR), A Case Study in Lower Mainland, BC

Mohammad Khandan Bakavoli [1*], Mehdi Hosseyni [1] and Mohsen Nicksiar [2]

[1] Senior Geotechnical Engineer, SNC-Lavalin Inc., Burnaby, BC, Canada

[2] Geotechnical Operations Manager-Lower Mainland, SNC-Lavalin Inc. Burnaby, BC, Canada

[*] mohammad.bakavoli@snclgroup.com (Corresponding Author)

ABSTRACT

The Canadian 6th Generation seismic hazard model, which has been developed by the Geological Survey of Canada (GSC), provides seismic hazard values for the 2020 National Building Code of Canada (NBCC2020). This seismic hazard model generally involves a significant increase to the spectral values compared to the 5th Generation presented in NBCC2015. A seismic upgrade assessment of a project in the Lower Mainland, BC, was performed using new seismic hazard values of NBCC2020. As part of this assessment, new sets of seismic motion records were prepared and scaled to the new building code uniform hazard response spectrum (UHS 2020), based on the code requirements. In this study, a sensitivity analysis was completed to assess the impact of time history scaling methods on the corresponding Cyclic Stress Ratio (CSR), and accordingly on the extent of liquefaction. Ground motion time histories were scaled to the target hazard of the site. Different methods of scaling and matching were employed including: (i) linear scaling to peak ground acceleration (PGA), (ii) Spectral Acceleration (SA) scaling at fundamental period of structure (T), (iii) scaling based on the integration of spectral acceleration equal to the area under the target response spectrum within the period range of interest (i.e. 0.15T-2.0T), (iv) scaling based on the mean square error between the spectral acceleration of the records and the target spectrum in the period range of interest, and (v) spectral matching in the time domain.

This paper presents results of different methods of scaling and compares their impact on CSR and extend of liquefaction at the project site.

Keywords: Seismic Ground Motion Scaling, CSR, Liquefaction, Spectral Matching

INTRODUCTION

The 6th Generation Seismic Hazard Model of Canada (CanadaSHM6) provides the basis for seismic design values proposed by Natural Resources Canada for the 2020 edition of the National Building Code of Canada (NBCC 2020) [1]. The new code came into effect in late March 2022. The earthquake time histories have to be compatible with the Uniform Hazard Spectrum (UHS) in accordance with the new code requirements to conduct seismic analyses [1].

The studied site was located in Lower Mainland, BC, which has a unique seismic setting that includes earthquakes from three different sources: shallow crustal earthquakes, which occur along shallow faults in the Earth's crust; inslab events, which occur deep within subducting tectonic plates; and subduction interface events, which are caused by slip between subducting tectonic plates (i.e., the North American Plate and the Pacific Plate) [2].

In this study, a sensitivity analyses were performed to study the impact of different scaling methodologies on dynamic response of the representative soil column such as Cyclic Stress Ratio (CSR), Response Spectrum (RS), and the resultant extent of liquefaction. Different method of scaling and matching were employed including:

(i) Linear scaling to peak ground acceleration (PGA);
(ii) Spectral Acceleration (SA) scaling at fundamental period of structure (T);

(iii) Scaling based on the integration of spectral acceleration equal to the area under the target response spectrum within the period range of interest (i.e. 0.15T-2.0T);
(iv) Scaling based on the mean square error between the spectral acceleration of the records and the target spectrum in the period range of interest; and
(v) Spectral matching in the time domain.

As currently, there is no specific UHS scenario available for the 6th generation seismic hazard values (such as Open file report 8090, by GSC [2]), only one UHS was considered. In the current study, the focus of sensitivity analyses was on the crustal earthquake time histories only.

UNIFORM HAZARD SPECTRUM FOR THE PROJECT SITE

The UHS2020 for the project site with the return period of 2,475 years (2% in 50 years) on the firm ground (V_{s30}=450 m/s) is shown in Figure 1. This UHS is the target spectrum for selection and scaling of the ground motions for the project site.

The red data points are obtained from Natural Resources Canada (NRCan) website [3], and the corresponding data is given in Table 1. A more refined definition of the UHS is required for the ground motion scaling process for smaller period intervals. Therefore, logarithmic interpolation, as described in clause A-4.1.8.4 of NBCC2020 [1], was used with an interpolation period of 0.005 seconds to provide more refined UHS shown in Figure 1.

Table 1.UHS for the Return Periods of 2,475 year (2% in 50 years)

Period(s)	**PGA (0.02s)**	**0.05**	**0.1**	**0.2**	**0.3**	**0.5**	**1**	**2**	**5**	**10**
5% Damped-Spectral Acceleration	0.428	0.62	0.9	1	0.955	0.714	0.411	0.255	0.0712	0.0315

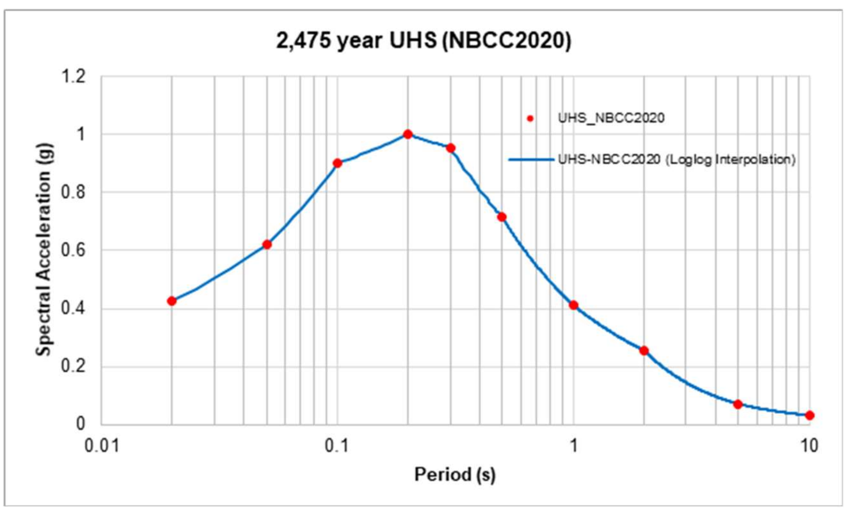

Figure 1. Uniform Hazard Spectra (UHS) for the project site

PERIOD RANGE FOR GROUND MOTION TIME HISTORIES SELECTION AND SCALING

In the process of selecting and scaling the ground motions, to the UHS, a period range of interest should be selected that sufficiently covers the periods of the modes of vibrations that contributes to the dynamic response of the structure. At this project site, the fundamental period of the structure is expected to be T1=0.8s to 1s.

In the absence of NBCC 2020 Commentaries, the Commentary J of NBCC2015 [4] was employed in this assessment. The latter states the period range (TR) should be considered between minimum (0.15T1, T90%) and maximum (2T1, 1.5s), for the purpose of time histories scaling. As per Commentary J, the period range for scaling of time histories should be 0.02s to 2s. Suites of ground motion records should be selected to cover appropriate segments of the period range of interest considering the dominant earthquake magnitude–distance combinations revealed by the site-specific seismic hazard disaggregation. Hence, it is considered that the crustal earthquake suite covers the period range of 0.02s to 1.5s in this assessment.

GROUND MOTIONS SELECTION AND SCALING METHODOLOGY

Ground Motions Selection Criteria

The earthquake motion records, for the purpose of this study, were selected from the Standard Exchange Earthquake Data (SEED). The SEED earthquake motions are typically selected based on the earthquake magnitude and source-to-site distance ranges that represent the earthquake scenarios which contribute most to the seismic hazard.

Once the scenario earthquakes are selected, recorded earthquake acceleration time-histories are chosen that have similar source, path, and site properties to the scenario earthquakes evaluated from the de-aggregation analysis. The time-history selection criteria generally include earthquake magnitude, source-to-site distance, tectonic settings faulting mechanism for different earthquake scenarios (i.e., reverse/oblique mechanism for Crustal earthquakes while normal faulting for deep inslab), rupture directivity, and near-surface ground condition at the recording station. Additionally, the overall shape of response spectrum of SEED records and the geometric mean of horizontal components should be comparable to the target UHS [4].

Ground Motions Databases

Shallow crustal earthquake records were obtained from the Pacific Earthquake Engineering Research Center (PEER)'s Next Generation Attenuation (NGA) West 2 database [5], which is a web-based ground motion database that includes a very large set of ground motions recorded worldwide for shallow crustal earthquakes in active tectonic regions.

Inslab earthquake records can be obtained from the US Geological Survey (USGS) National Strong Motion Program (NSMP), and Consortium of Organizations for Strong-Motion Observations Systems (COSMOS). All these databases were gathered in Center for Engineering Strong Motion Data (CESMD) website [6]. However, interface earthquake records can be obtained from Japanese K-Net/KiK-Net strong motion network [7], and University of Chile Seismic Network [8].

Some of the selected records had been already processed and corrected, however signal processing had to be applied to the other records including a baseline correction to the acceleration time series, and a 4th order band-pass Butterworth filtering with corner frequencies of 0.1Hz and 25Hz.

As the sensitivity analyses was only focused on shallow crustal earthquakes, the table 2 only contains the crustal earthquake suite.

Table 2. Parameters of Selected Crustal Earthquake Time Histories (2,475 year Return Period)

Record_ID	Event Name	Station	RSN	Mw	R (km)	Site Type/Vs (m/s)	Component
Crustal01_H1	San Fernando, 1971	Pasadena - CIT Athenaeum	79	6.6	25.47	415.13	000
Crustal01_H2	San Fernando, 1971	Pasadena - CIT Athenaeum	79	6.6	25.47	415.13	090
Crustal02_H1	Loma Prieta, 1989	Capitola	752	6.9	15.23	288.62	000
Crustal02_H2	Loma Prieta, 1989	Capitola	752	6.9	15.23	288.62	090
Crustal03_H1	Northridge, 1994	LA - Wonderland Ave	1011	6.7	20.29	715.12	095
Crustal03_H2	Northridge, 1994	LA - Wonderland Ave	1011	6.7	20.29	715.12	185
Crustal04_H1	Chi-Chi_ Taiwan, 1999	TCU047	1487	7.6	35	520.37	EW
Crustal04_H2	Chi-Chi_ Taiwan, 1999	TCU047	1487	7.6	35	520.37	NS
Crustal05_H1	Landers, 1992	North Palm Springs Fire Sta #36	3757	7.3	26.95	367.84	090
Crustal05_H2	Landers, 1992	North Palm Springs Fire Sta #36	3757	7.3	26.95	367.84	180

METHODOLOGY FOR GROUND MOTIONS SCALING

Two methodologies proposed by Commentary J of NBCC2015 [4] to linearly scale ground motions, namely Method A and Method B. In Method A, a single target response spectrum is specified based on the design spectrum and period range of interest, then suites of ground motion records to be selected to cover appropriate segments of the period range, considering the dominant earthquake magnitude‑distance combinations revealed by the site-specific seismic hazard disaggregation. While in in Method B, two or more site-specific scenario target response spectra may be specified to cover the period range of interest. Each target spectrum is used to select and scale the specific suites of ground motion records, considering earthquake magnitude‑distance combinations and tectonic sources used to define the scenario target spectra.

The geometric mean spectrum of the selected scaled ground motions should not fall below 90% of UHS at any period within the scenario-specific period range (Commentary J, NBCC2015 [4]). In the current study, method A was used. The following steps were applied to the horizontal ground motion time histories:

- Each horizontal components of the selected records were scaled over the scenario-specific period range. In the mean square error method, both of two components for each earthquake scaled using one scaling factor.
- The geometric mean spectrum of the selected ground motions should not fall below 90% of UHS at any period within the scenario-specific period range (Commentary J, NBCC2015 [4]).
- Accordingly, where the mean spectrum of the selected motion fell below 90% of the UHS at any point in the period range specified in **Error! Reference source not found.**, a global scaling factor was used to raise the mean spectrum to comply with Commentary J, NBCC2015 requirements.

PGA Scaling

One approach which is frequently employed to adjust a time history to match a specific spectrum, is known as PGA scaling [9]. By using this technique, the chosen record is multiplied by a scalar coefficient to ensure that the peak ground acceleration (PGA) of the scaled record is equivalent to the PGA of the target spectrum. Despite the effectiveness of this method, it does not account for the frequency content or spectral shape of the accelerogram. Consequently, although all PGA scaled ground motions have the same PGA, their response spectrum can vary widely across different periods, as demonstrated in Figure 2. For this project site, the NBCC2020 recommends a PGA of 0.428g.

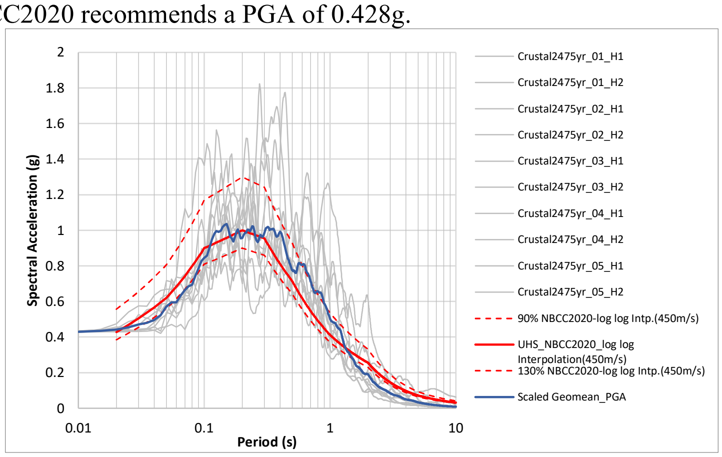

Figure 2. Uniform Hazard Spectra (UHS) and the Earthquake Time Histories Scaled by PGA

Scaling at Fundamental Period of Structure

The purpose of this approach is to employ a multiplier that adjusts the records in a way that their spectral acceleration at the fundamental period of the structure corresponds to the target spectral acceleration at that period. As a result, a series of scaled time sequences are generated, all of which exhibit identical spectral acceleration at the structure's fundamental period [10]. However, the usage of this method can be problematic since it may result in decreased precision at higher modes of vibration due to yielding. Furthermore, relying solely on one particular period for scaling the records may not provide an accurate representation of their strength and frequency content. After implementing the method, as the geometric mean of the spectrum of the scaled ground motions falls below 90% of UHS a global scaling factor of 1.3 was applied to raise the mean spectrum to comply with code requirements.

Figure 3 demonstrates the spectral response of the time histories that have been scaled using this technique at T1=0.8 sec, which is the natural period of the system. The response spectrum of these scaled ground motions reveals a broad range in spectral accelerations.

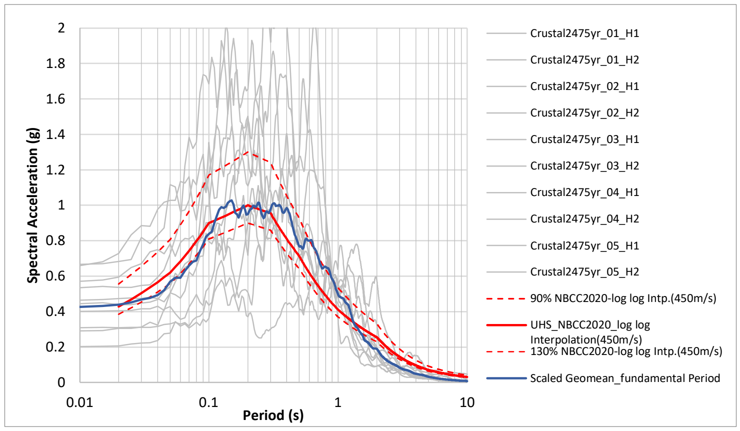

Figure 3. Uniform Hazard Spectra (UHS) and the Earthquake Time Histories Scaled at Fundamental Period of Structure

Scaling to the Area Under Uniform Hazard Spectrum Between the Period Range of Interest

This method consists of computing the area under response spectrum. This involves integrating spectral accelerations within the period range of interest [10]. The ground movements must be adjusted so that the area under the response spectrum is equivalent to the area beneath the UHS within these two periods. As the geometric mean of the spectrum of the scaled ground motions, using the UHS integration, falls below 90% of UHS a global scaling factor of 1.2 has been applied to elevate the mean spectrum to comply with code requirements. Figure 4 shows the mean scaled time histories compared to uniform hazard spectrum for the project site.

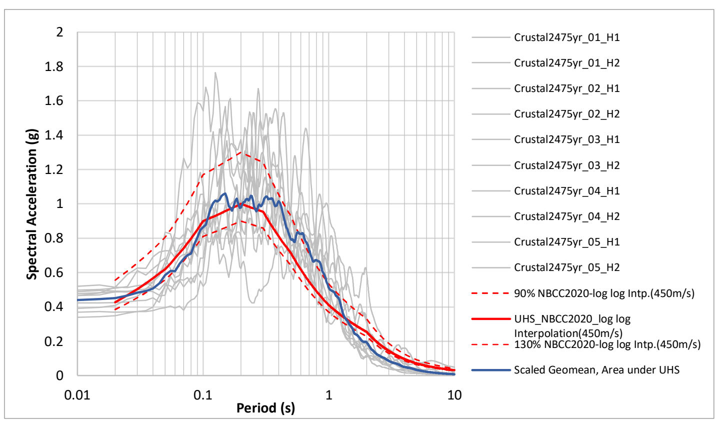

Figure 4. Uniform Hazard Spectra (UHS) and the Earthquake Time Histories Scaled to Area under the UHS Spectrum

Scaling Based on the Mean Square Error

This approach employs the Mean Squared Error (MSE) as a quantitative measure to assess how well a recorded time history aligns with a target spectrum [5]. To accomplish this, the period range of interest is divided into numerous equally spaced points, and the target and recorded response spectra are interpolated to obtain spectral acceleration at each respective period. Subsequently, the MSE is calculated over the user-specified period using the following equation:

$$\mathbf{MSE} = \frac{\sum_i w(Ti)\{\ln[Sa_{target}(Ti) - \ln[fS\ _{response}(Ti)]\}^2}{\sum_i w(Ti)} \quad (1)$$

where $w(Ti)$ is a weight function allowing the user to apply different weight to some periods of greater interest, is the spectral $Sa_{target}(Ti)$ acceleration of the target spectrum, $Sa_{response}(Ti)$ is the spectral acceleration of the ground motion being scaled, and f is a linear scaling factor applied to the entire response spectrum [5]. As the geometric mean of the spectrum of the scaled ground motions, using the UHS integration, falls below 90% of UHS, for periods of less than 0.1s, a global scaling factor of 1.06 has been applied to raise the mean spectrum to comply with code requirements, as illustrated in Figure 5.

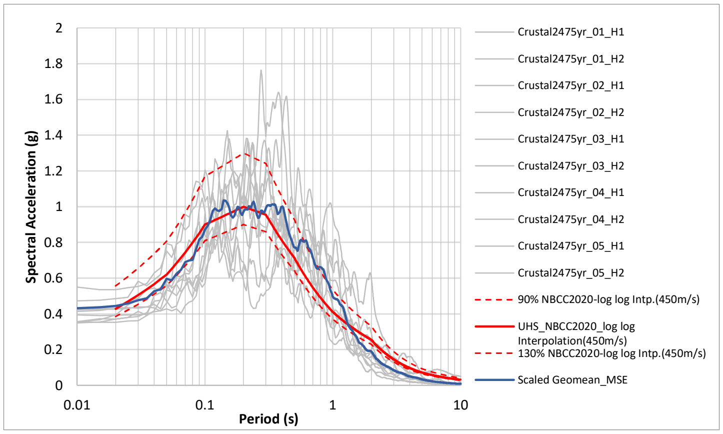

Figure 5. Uniform Hazard Spectra (UHS) and the Earthquake Time Histories Scaled Using Mean Square Error Method

Spectral Matching

Spectral matching is the term used to describe the process of adjusting an initial SEED earthquake ground motion in order to achieve a response spectrum that closely resembles a target response spectrum. The ultimate goal of this process is to minimize the peaks and valleys of the initial SEED motion's individual spectral components, while still retaining the motion's non-stationary attributes, as noted in Abrahamson 1992 [11].

Spectral matching can be executed using either the time or frequency domain approach. When performed in the frequency domain, the Fourier amplitude spectrum is adjusted, which can potentially distort the velocity and displacement time-histories and generate motions with high energy content, as mentioned in Hancock et al.'s 2006 research [12]. On the other hand, time-domain spectral matching involves adding wavelets to the time domain to enhance the seed motion's spectral deficiencies. By doing so, less energy is introduced into the acceleration time-history, and the initial time-history's non-stationary characteristics are preserved, as noted in the same study [12]. Each wavelet is applied to the time-history so that the time of the maximum spectral response in the adjusted time-history corresponds to the maximum spectral response in the unadjusted time-history. The primary assumption is that the peak response remains constant after the wavelet adjustment, as outlined in Hancock et al.'s 2006 findings.

To perform spectral matching in this particular investigation, RSPMatch09 was used, a computer program designed by Al Atik and Abrahamson in 2010 [13]. The software utilizes a time-domain matching technique originally developed by Lilhanand and Tseng in 1988 [14], which was subsequently revised by Abrahamson in 1992, Hancock et al. in 2006, and Al Atik and Abrahamson in 2010. Figure 6 depicts the earthquake time histories spectrally matched to UHS for the project site for the period range of 0.02s to 1.5s.

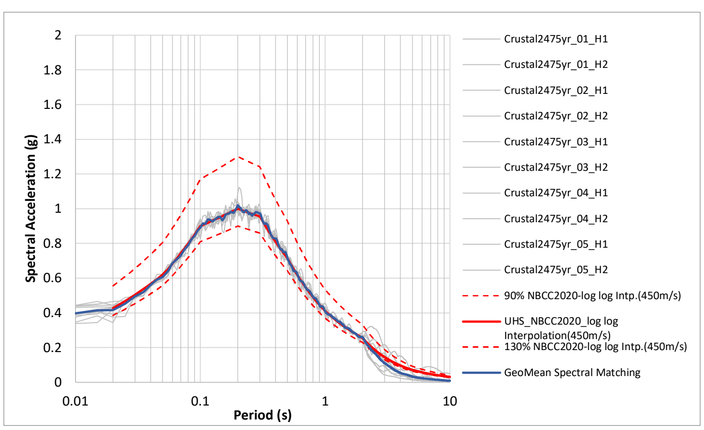

Figure 6. Uniform Hazard Spectra (UHS) and the Earthquake Time Histories Spectrally Matched to UHS

SITE RESPONSE ANALYSES

The local soil conditions and depositional regime have a profound influence on the ground response during earthquake events. Type, thickness, and geometry of depositional soil may amplify or de-amplify the underlying motion on the ground surface. Hence, a One-Dimensional (1-D), equivalent-linear (total-stress) site-specific ground response analysis (using SHAKE2000) was conducted to evaluate the impact of the local soil conditions on the motions traveling from the firm ground to the ground surface.

To understand the effect of different time histories scaling methodologies on the dynamic response of the site, equivalent linear using SHAKE 2000 and Non-linear analyses using PLAXIS 2D were carried out.

Soil Stratigraphy

The soil layers, for the project site, generally consisted of loose to very loose layer sand and gravel, compact to dense sand and gravel, and dense to very dense sand and gravelly layer, overlain by Till-Like material. Due to absence of direct shear wave velocity measurements, various correlations were used to estimate shear wave velocity (V_s) for sandy and gravelly layers using the average Standard Penetration Test (SPT) blow counts. The correlations presented in PEER report by Wair et al. 2012 [15], Washington Department of Transportation (WSDOT) were employed to estimate shear wave velocity of the project site. From different correlations presented in those documents, correlations by Dikmen 2009 [16], Hasancebi and Ulusay 2007 [17], and Pitilikas 1997 [18] were used for the purpose of this study. Depth of firm ground was considered to be at 56m depth based on the available information at the site. The Shear wave velocity profile for the project site is illustrated in Figure 7.

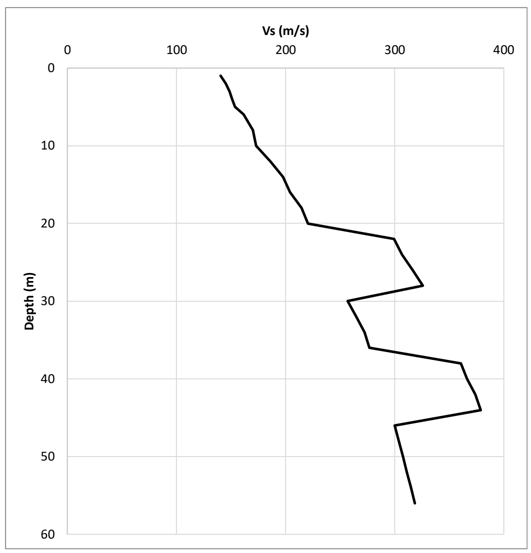

Figure 7. Representative Shear Wave Velocity Profile

Soil Parameters and Models Used in SHAKE2000

Equivalent-linear total-stress one-dimension (1-D) approach was completed using SHAKE2000 program (version 10.01.9000 developed by GeoMotions, LLC). The analyses were performed in the frequency-domain for non-liquefied ground conditions to determine the motion characteristics (i.e., ground accelerations, strains) at ground surface, for 5% damping. An equivalent shear strain (effective strain), i.e., 65% of the maximum shear strain, was considered to select the corresponding shear modulus and damping according to a selected degradation and damping curve (Idriss and Sun 1992 [19]).

In the equivalent-linear analyses, the shear modulus and damping for each layer are presented in Table 3, and considered to be constant throughout the earthquake duration at each iteration. Since this is an elastic analysis with degraded shear modulus, permanent deformation cannot be accounted for (i.e., upon cessation of the seismic motion, the system returns to its initial, nondeformed position). Equivalent viscous damping simulates the effects of hysteretic material damping. To minimize the layer thickness effect on the wave propagation and the non-linear calculations in SHAKE2000, the thickness was limited to 1/8 to 1/5 of the shear wavelength according to Kulemeyer and Lysmer (1973) [20].

The modulus reduction and damping curves used in ground response analyses were chosen based on the available information within each soil unit as presented in Table 3.

Table 3. Soil Units, Modulus and Damping Reduction Curves

Material	Depth (m)	G/Gmax Reduction Curve	Damping Curve
Sand	0 m-20 m	Sand Upper G/Gmax – SAND, Upper Bound (Seed & Idriss 1970)	Sand lower Damping for SAND, Lower Bound (Seed & Idriss 1970)
Sandy gravel	20 m-28 m	Gravel Avg. G/Gmax – GRAVEL, Average (Seed et al. 1986)	Gravel Damping for GRAVEL, Average (Seed et al. 1986)
Sand	28 m-36 m	Sand Upper G/Gmax – SAND, Upper Bound (Seed & Idriss 1970)	Sand lower Damping for SAND, Lower Bound (Seed & Idriss 1970)
Sandy gravel	36 m-44 m	Gravel Avg. G/Gmax – GRAVEL, Average (Seed et al. 1986)	Gravel Damping for GRAVEL, Average (Seed et al. 1986)
Sand	44 m-56 m	Sand Upper G/Gmax – SAND, Upper Bound (Seed & Idriss 1970)	Sand lower Damping for SAND, Lower Bound (Seed & Idriss 1970)
TILL	Below 56 m	EPRI 121-250'G/Gmax Deep Cohesionless Soils – Depth 121-250 feet (36-75 m) (EPRI, 1993)	EPRI 121-250' Damping Deep Cohesionless Soils – Depth 121-250 feet (36-75 m) (EPRI, 1993)

Non-linear Effective Analyses Using PLAXIS

Liquefaction assessment was completed using results of equivalent-linear analyse. However, since the equivalent-linear method is not valid for layers with high strain, a non-linear analysis is required to capture soil non-linearity. Hence, the non-linear effective-stress 1-D analyses were performed for a column of soil using PLAXIS 2D program (Connect Edition version 21.01.00.479 developed by Bentley). The analyses were performed in the time-domain for non-liquefied and liquified ground conditions to determine the motion characteristics at the ground surface, for 5% damping. The analyses were completed for the sets of earthquake time-histories which were scaled using different techniques.

The HSsmall (Hardening Soil Model with small-strain stiffness) elastoplastic type of hyperbolic model was used for modelling non-liquified ground conditions. The UBC3D-PLM model developed by University of British Columbia was used to capture liquefied ground conditions. The results of liquefaction analyses are compared and presented in Table 4.

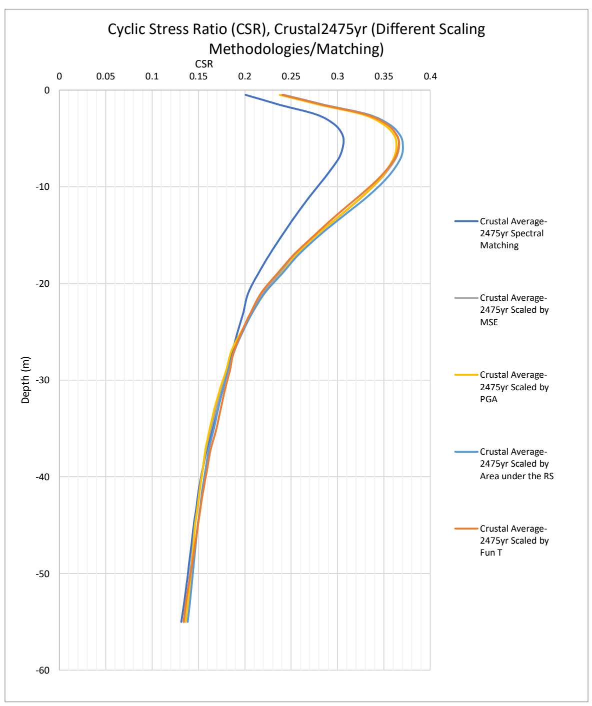

Figure 8. Cyclic Stress Ratio (CSR) Using Different Scaling Methodologies and Spectral Matching

RESULTS AND DISCUSSIONS

Figure 8 illustrates various CSR profiles obtained through equivalent-linear methods, which were compared to examine the impacts of different scaling methodologies. The CSRs obtained from distinct scaling techniques show a striking resemblance, as they meet the minimum requirements specified by the NBCC2020. However, the CSR obtained using the spectrally matched technique exhibits lower values, particularly for shallow depths.

Due to the low shear strength soil layers, particularly at shallow depths at the site, there is a slight variation in the extent of liquefaction observed using the motion time-histories with different scaling techniques. The extent of liquefaction for different scaling techniques for the equivalent-linear and non-linear are presented in Table 4.

Table 4. Extent of Liquefaction for Different Scaling/Matching Techniques

Scaling/Matching Technique	**Extent of Liquefaction**	
	Equivalent Linear	Non-Linear
PGA Scaling	0-27m	2m-25m
Scaling to the Fundamental Period	0-27m	2m-25m
Scaling to the Area under UHS	0-27m	2m-25m
Scaling Based on the MSE	0-27m	2m-25m
Spectral Matching	0-25m	2m-23m

The liquefaction analyses indicate that the time-history motions scaled using Spectral Matching results relatively smaller extend of liquefaction.

Figure 9 illustrates the average response spectra generated using various scaling/matching techniques, which is another useful output from site response analyses for the engineering design purposes. This figure includes the 2020 NBCC seismic hazard values that correspond to the average shear wave velocity of the top 30m, which is 205m/s, as well as the Site Class C (Vs=450m/s) spectral acceleration. The response spectrum produced using spectrally matched earthquake time histories exhibits relatively lower spectral values than other time-histories for the period range less than 0.135s. It is evident, that response spectra developed using these motion records results in a meaningful smaller average spectral value within the structure fundamental period range (i.e. 0.8s to 1s) which impact the seismic demand load for the civil and structural design

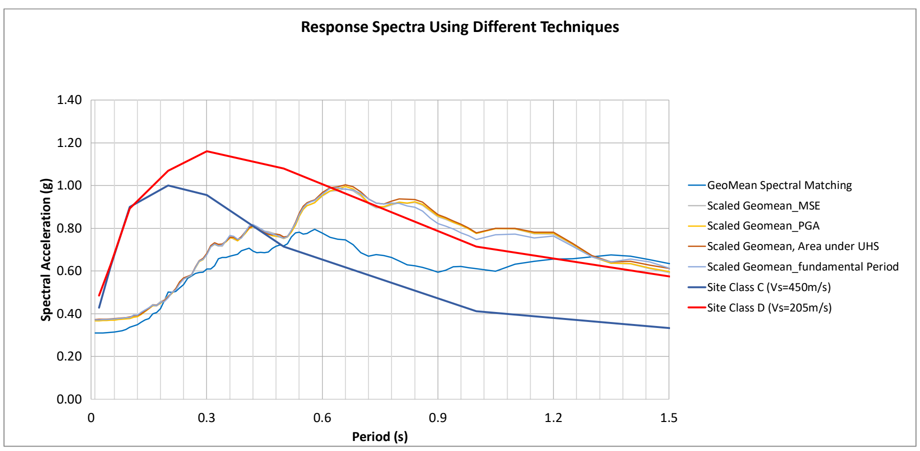

Figure 9. Comparison of Response Spectrum Using Different Scaling Methodologies and Spectral Matching

CONCLUSION

The seismic performance of a typical soil column located in the Lower Mainland, BC was studied for 2475-year "Crustal Earthquake" motions which were developed using various ground motion scaling/matching methods to the uniform hazard spectrum. Results of this study indicated that the spectrally matched earthquake time histories produced less variability in the results compared to the other scaling techniques, as this method attempts to generate earthquake records that closely match the response spectrum of the uniform hazard spectrum. Consequently, this approach resulted in lower CSR and spectral values. While, the effect of scaling/matching technique was not significant in the extent of liquefaction for the study site since the upper soil layers were mostly composed of low shear strength layers. It is worth noting that while spectral matching was employed for the earthquake time histories, the response spectrum had a 15-20% decrease compared to linearly scaled earthquake motions.

The other components of seismic performance of the project site were studied, however, due to various restrictions were not presented in this paper.

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