Impacts of ground motion and scaling method selection on the performance of rocking wall systems with friction connections

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ABSTRACT

Dynamic time-history analysis has long been regarded as an acceptable and reliable method for seismic design of structures not covered by codal guidelines and often referred to as "alternative" design. Resilient rocking wall systems with low-damage hold-downs fall within the 'alternative' design category for most international standards such as NZS1170, ASCE7 and NBC2020 and design must include dynamic time-history analysis. There are, however, factors that affect the analysis result including the selection of the ground motions, record scaling method, and assumptions used in the numerical model. In addition to codes providing guidance on selecting and scaling records, there are research studies that propose new or improved methods for selecting and scaling records. This paper focuses on the investigation of the impact of selection and scaling of ground motions on the structural response of selected mass timber archetype rocking wall system with friction connections. An investigation of the selection of records examines three main tectonic sources of ground motions and evaluates their impact on the response of the rocking system. Furthermore, an evaluation and comparison of the system response is conducted using three major and common scaling methods, namely amplitude scaling, spectral matching, and mean spectrum matching. In addition, these alternatives selections are examined with regard to their impact on the system's higher mode effects.

1 INTRODUCTION

Shear walls and rocking walls have long been recognized for their ease of construction and high reliability, demonstrating outstanding performance in seismic events over recent decades. Only a very small proportion of such structures have collapsed or sustained catastrophic damage. There has been a great deal of advancement in the field of rocking wall systems in recent years both for concrete and mass timber sector. In part, this is due to the fact that a rocking wall is more efficient and capable of dissipating energy through controlled rocking, regardless of whether it is coupled or decoupled from gravity. Generally, the rocking wall, as a result of its own weight or further gravitational load, will return to its original position and re-center. Furthermore, it can be combined with additional seismic performance-enhancing systems, such as post-tensioning or low-damage friction hold-downs, in order to enhance seismic performance and increase energy dissipation capacity. Numerous numerical studies and experimental studies have been conducted to evaluate and investigate the performance of such innovative and resilient systems and many have shown great potential, and some have been implemented in real life projects and structures. Despite this, such innovative systems are limited in that current seismic codes such as NZS1170, ASCE7, and NBC2020 do not address or provide provisions for the design of such systems. As a result, such systems are presently categorized under the 'alternative' system category. For the design of an 'alternative' systems, Dynamic Time History Analysis (DTHA) is the prescribed and acceptable method. It is also subject to peer review. Rocking wall systems exhibit highly dynamic and non-linear responses and the higher mode effects become more prominent with increasing height. DTHA allows for the simulation of these complex behaviours under varying ground motions, which are difficult to capture accurately with simpler, more conventional analysis methods. There are, however, factors that affect the analysis result including the selection of the ground motions, scaling method, and assumptions used in the numerical model. In addition to codes providing guidance on selecting and scaling records, there are research studies that propose new or improved methods for selecting and scaling records. This paper focuses on the investigation of the impact of selection and scaling of ground motions on the structural response of selected archetype rocking wall system with low-damage friction hold-downs which has gained momentum in recent years specially in the field of mass timber buildings. This paper provides valuable insights for those interested in adopting friction connections for low damage design of rocking wall structures.

1.1 Ground Motion Scaling

Ground motion recordings from large and rare events are scarce. Hence, designers often utilise records from smaller events which are more abundant by nature. Each record is individually scaled to the intensity of the larger ‘design earthquake’ event. This is illustrated in Figure 1.

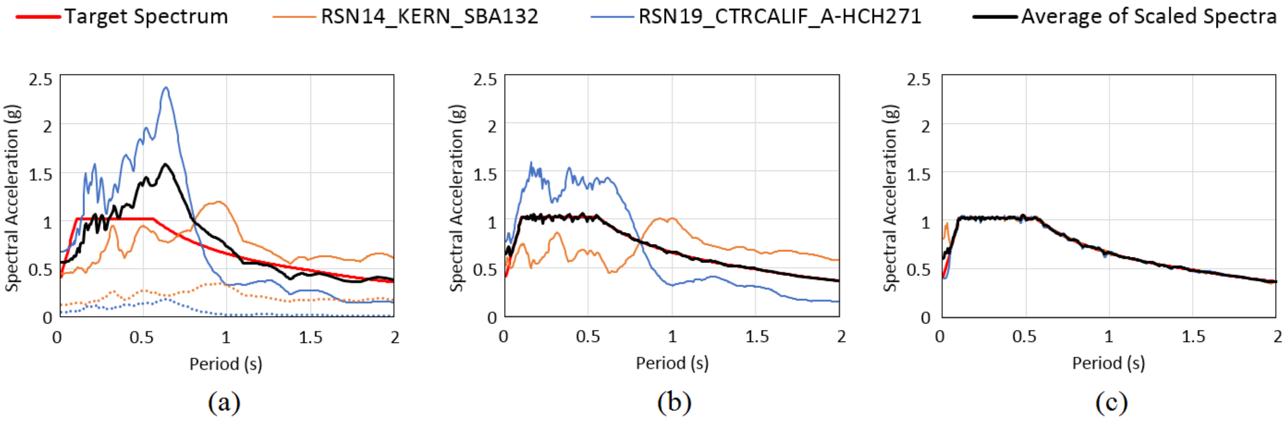


Figure 1. (a) Amplitude scaling. (b) Mean-spectrum matching. (c) Spectral matching.

Figure 1(a) depicts two records that have been amplitude scaled (Zhang et al. 2020). Equation 1 shows the scale factor SF_{S_a} required to produce the best fist between the record’s response spectrum $S_a^{unscaled}$ and the target response spectrum S_a^{target}. This value is by minimising the sum of squared errors SSE_{S_a} in Equation 2.

$$\boldsymbol{SF_{S_a}} = \frac{\sum_{i=1}^{N}\left[\boldsymbol{S_a^{unscaled}(T_i)\cdot S_a^{target}(T_i)}\right]}{\sum_{i=1}^{N}\left[\boldsymbol{S_a^{unscaled}(T_i)}\right]^2} \tag{1}$$

$$SSE_{S_a} = \sum_{i=1}^{N} \left[SF_{S_a} \cdot S_a^{unscaled}(T_i) - S_a^{target}(T_i) \right]^2 \tag{2}$$

Alternatively, the scale factor $SF_{\ln S_a}$ shown in Equation 3 applies when scaling in logarithmic ordinates to minimise the error $SSE_{\ln S_a}$ shown in Equation 4. This is the preferred method in some design codes like NZS 1170.5 and NBC2015 because ground motion responses assume a lognormal distribution (Bradley 2012). However, for practical purposes other design codes employ scaling in linear coordinates, which emphasise a better fit across the shorter periods.

$$SF_{ln\,S_a} = exp\left(\frac{1}{N}\sum_{i=1}^{N}\left[ln\,S_a^{target}(T_i) - ln\,S_a^{unscaled}(T_i)\right]\right) = \left[\prod_{i=1}^{N}\frac{S_a^{target}(T_i)}{S_a^{unscaled}(T_i)}\right]^{\frac{1}{N}} \tag{3}$$

$$SSE_{ln\,S_a} = \sum_{i=1}^{N}\left[ln\left(SF_{ln\,S_a}\cdot S_a^{unscaled}(T_i)\right) - ln\left(S_a^{target}(T_i)\right)\right]^2 \tag{4}$$

Designers are often interested only in the mean or median response across several ground motions. As shown in Figure 1(c), spectral matching achieves this purpose by suppressing the variance and this enables a quicker convergence on the mean or median with fewer analyses (Bazzurro and Luco 2006). Essentially, spectral matching modifies the ground motion record by inserting a series of n wavelets at the time of peak responses corresponding to the n oscillator periods. Thus, the peak responses at n periods can be adjusted. The magnitude of each wavelet is determined such that their combined effect provides the necessary adjustment at each of the n periods (i.e., the difference between the scaled and target response spectra). More formally, the spectral matching procedure is described by Equations 5 and 6 (Al Atik and Abrahamson 2010). The element $\boldsymbol{c_{ij}}$ in the matrix $\mathbf{C}$ represents the peak response of an oscillator with period i, when subjected to a wavelet of unit amplitude and period j. In other words, it quantifies how each of the n oscillators respond to all n individual wavelets. The summation of these responses must satisfy the adjustments required by vector $\mathbf{R}$ across all n periods simultaneously. Hence, the magnitudes of the wavelets $\mathbf{b}$ are found by solving this system of simultaneous equations.

$$\mathbf{Cb} = \Delta\mathbf{R} \tag{5}$$

$$\begin{bmatrix} c_{11} & \cdots & c_{1n} \\ \vdots & \ddots & \vdots \\ c_{n1} & \cdots & c_{nn} \end{bmatrix}\begin{bmatrix} b_1 \\ \vdots \\ b_n \end{bmatrix} = \begin{bmatrix} \Delta R_1 \\ \vdots \\ \Delta R_n \end{bmatrix} \tag{6}$$

One argument against spectral matching is that the loss of record-to-record variability can be unconservative. Because of this, ASCE 7-22 penalises spectral matching by requiring a target spectrum that is 10% higher. Mean-spectrum matching attempts to strike a middle ground between the two extremes of amplitude scaling and spectral matching. The goal is to ensure that the mean-spectrum (averaged across all records) matches the target spectrum while preserving the variability between record-to-record (Mazzoni et al. 2012b; Mazzoni et al. 2012a). This requires a linear scaling of the set of records, period-by-period, by the individual differences between the mean-spectrum and target spectrum as shown in Figure 1(b). To achieve this, the procedure begins by amplitude scaling all records to give an approximate fit and avoid excessive alteration from matching. The mean-spectrum is calculated as the average of all records' spectra. Next, find the set of n scale factors needed to match the mean-spectrum to the target spectrum at each of the n periods. Now, spectral matching is performed for each record, except that the adjusted spectrum (and hence, the input ΔR) is determined by the individual record's spectrum multiplied by the set of n scale factors at n period points. By doing this for all records, the mean-spectrum is shifted by the scale factor corresponding to each of the n period points. Thus, the records are only lightly modified by spectral matching.

1.2 Ground motion selection

Traditionally, the ground motions selected for structural analyses would possess similar seismological (tectonic source and site) characteristics as the seismic hazard expected for the structure (Stewart et al. 2002). However, engineering parameters like the response spectrum is known to correlate better with structural response quantities (Iervolino and Cornell 2005). This is also acknowledged by design codes like ASCE/SEI 7-22 which allow a looser match of the seismological parameters if a better match of spectral shapes is possible. Some regions like southwest British Columbia can be exposed to earthquakes arising from multiple types of source mechanisms (tectonic source) simultaneously, namely, shallow crustal, subduction interface and subduction intraslab mechanisms (Tremblay 1998). Similarly, New Zealand has faults that exhibit these main tectonic mechanisms and characteristics. In New Zealand these faults have all been identified and zones have been defined (Burlotos et al. 2022; Oyarzo-Vera et al. 2012). Large-magnitude subduction earthquakes are thought to produce longer shaking duration that induce a larger number of inelastic cycles on the structure (Chandramohan et al. 2016). Thus, it may not be sufficient to select ground motions based on the fit of the response spectrum alone, since it indicates the peak response only and does not offer any information on the number of cycles expected.

2 METHODOLOGY

2.1 Selected archetype and numerical modelling

This paper presents a two-dimensional model of a ten-storey mass timber structure with two rocking walls in ETABS (Computers and Structures Inc). As of now, engineers have only succeeded in constructing mass timber buildings of eleven storeys in earthquake prone regions, and any structure higher seems to be neither economical, effective, nor logically feasible. In (Assadi et al. 2023) study on rocking CLT walls with friction hold-downs, higher mode effects were shown to become evident after six stories. Therefore, a ten-storey building would be ideal in capturing these higher mode effects and highlighting the purpose of this study. The structure consists of ten storey gravity frame made of Glulam columns and Laminated Veneer Lumber (LVL) beams, measuring 41 meters wide and consisting of seven bays (Figure 2). Two balloon-type Cross Laminated Timber (CLT) rocking walls are offset (de-coupled) from the gravity frame in bays number two and five. The five-layered CLT rocking walls are constructed from Machine Stress Graded (MSG) sawn timber with a modulus of elasticity of 8 GPa in the longitudinal direction and 6 GPa in the transverse direction. All subsequent floors measure an equal height of 3.8 meters, except the first floor, which measures 4.8 meters, making the total height of the structure and rocking walls 39 meters. The building is assumed to be located in Wellington with hazard factor Z=0.4 and considering 1/500 earthquake event. Considering the low-damage design and philosophy applied in the design and modelling of the structure, a conservative S_P value of 0.85 is considered for this study. Loading considerations are based on a mix of residential and commercial structures. There is a dead load of 2.75kPa on all floors and a live load of 3kPa on all floors except for the roof, which carries a dead load of 1.7kPa and a live load of 1kPa. Self-weight of the members and the structure is calculated automatically by ETABS. As the mass timber gravity frame completely supports the gravity load, rocking CLT walls are decoupled from the gravity load resisting system in this study. The rocking walls utilize flag-shaped friction hold-downs to provide energy dissipation, self-centering, and allow safe rocking movement of the wall. It has been demonstrated through tests with rocking CLT walls and flag-shaped friction hold-downs that the combined rocking and friction joints deliver outstanding seismic performance, providing self-centering, and damage-free deformation and ductility (Hashemi et al. 2018; Hashemi et al. 2020). To ensure adequate load transfer to the walls, shear key links have been modelled between the frame structure and the rocking walls at every level. These shear key links transfer lateral loads to the walls while simultaneously allowing uplift and upward movement of the wall, preventing displacement incompatibility with the floor or beam (Assadi et al. 2023). It is important to emphasize that the gravity frame only transfers gravitational demand

and does not bear lateral demand except for transferring this demand to the walls, as all beams are released at both ends and column bases are pinned. Systems entire nonlinearity is contained within rocking of the CLT walls i.e. the flag-shaped friction hold-downs. In the ETABS model, effective section properties were implemented based on the FPI Innovation Modelling Guide (Chen et al. 2022) and the (Karacabeyli and Gagnon) handbook, and stress checks were conducted to ensure stresses were within elastic limits. Flag-shaped friction wall hold-downs are modelled using “Damper-friction spring” and rocking toes are modelled using non-linear “Gap” link elements in ETABS (Hashemi et al. 2020). In practice, to facilitate the rotation of the hold-downs in line with the rocking wall, a spherical swivel bearing will be used at the base of the friction hold-downs. Therefore, in the numerical model, a pinned boundary condition is assigned at the bottom of the damper-friction spring links. In this model, the Newmark (Wilson 1998) and Hilber-Hughes-Taylor (CSI Analysis Reference Manual) integration algorithms are implemented and tested, and it is later concluded that the Hilber-Hughes-Taylor method, which employs an alpha value other than zero ($0<\alpha<-0.33$), creates an energy error in the analysis and is therefore not appropriate for this archetype DTHA. A conservative 2% Rayleigh damping is pivoted at first mode (fundamental mode) and second mode, respectively, and the mass is lumped at each storey by default via ETABS (CSI Analysis Reference Manual). Through ETABS, the key time periods of the structure and their mass participations have been calculated based on the effective stiffness of the flag-shaped friction hold-downs. A mode 1 time period of 1.99 seconds, a mode 2 time period of 0.355 seconds, and a mode 3 time period of 0.144 seconds were determined with mass participation ratios of 69%, 20%, and 6%, respectively. Due to the fact that the case study structure is considered a tall structure, non-linear pushover analysis is not appropriate for this study, as the first three modes of vibration have a significant effect on the structure's response (not just the first mode), and the fundamental time period exceeds one second (MBIE 2018).

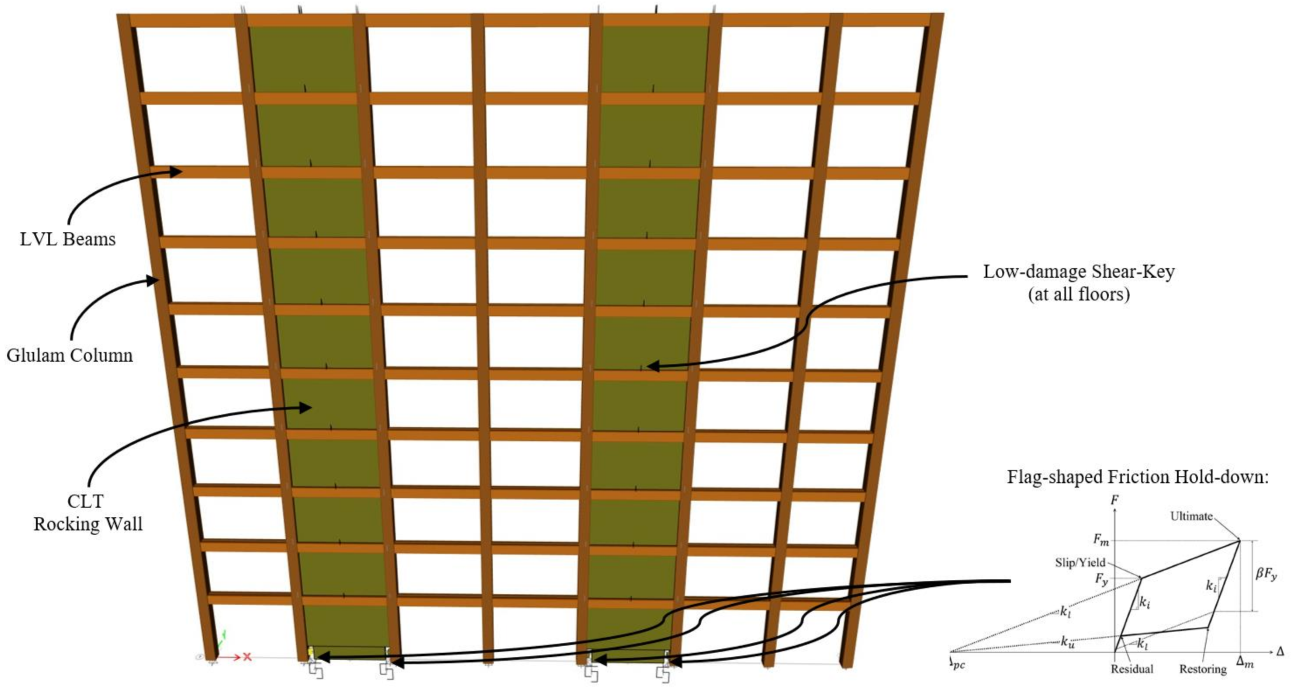
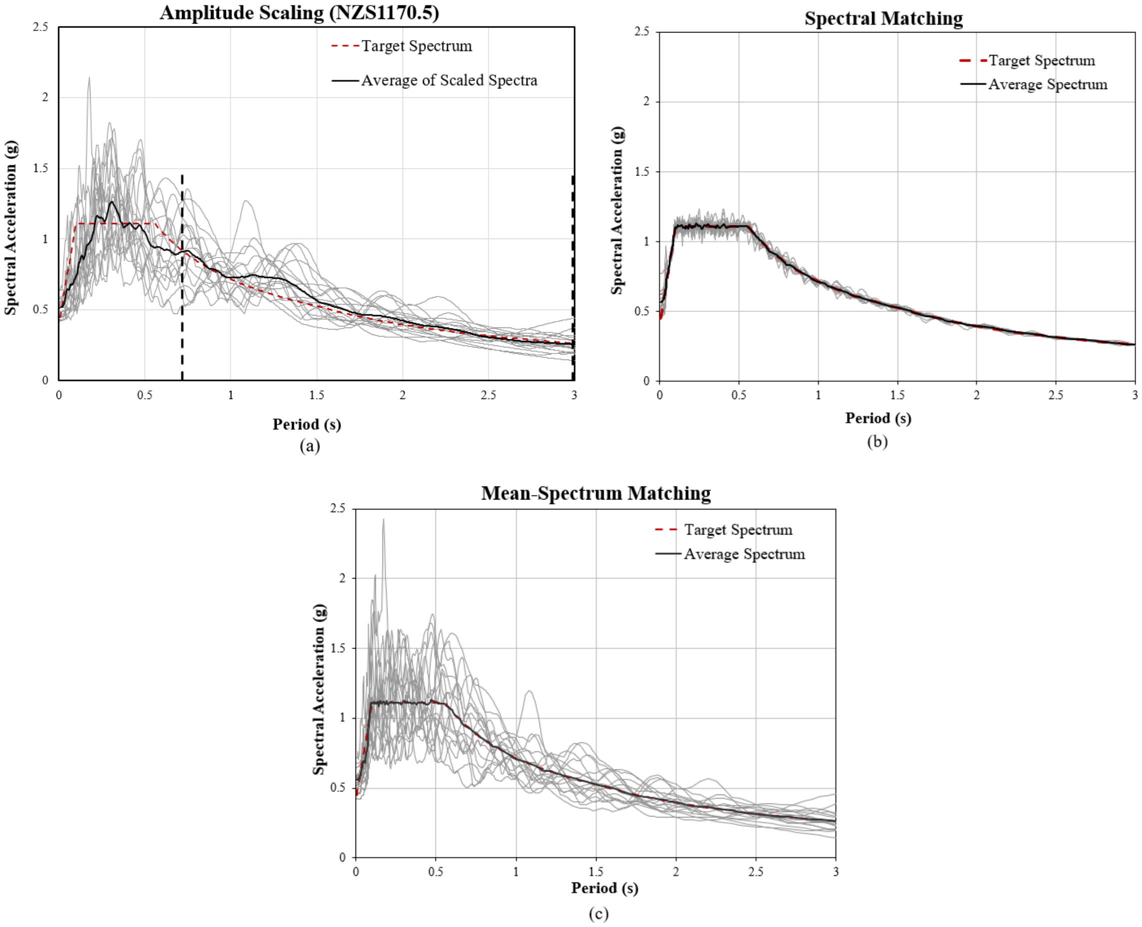


Figure 2. Selected archetype and numerical modelling of ten-storey mass timber structure with balloon type CLT rocking walls, utilizing flag-shaped friction damper hold-downs.

The investigation of this paper can be divided into two parts. In one part the impact of scaling method of ground motion is investigated, and in the other part the impact of ground motion source and characteristics is investigated. The information presented herein holds significant relevance and utility, particularly in the context of New Zealand, which encompasses fault characteristics of the three principal tectonic sources delineated in Section 1.2.

2.2 Ground motion scaling

For this purpose, 14 records from PEER NGA-West2 data base have been selected in which fit the best within the scaling criteria prescribed by NZS1170.5. The amplitude scaled time period of interest spans from the minimum period that captures combined vibrational modes representing 90% of mass participation, extending to a maximum period equal to 1.5 times the first mode of vibration, T_1. In order to conduct comparable comparisons, similar criteria have been selected for all the records. All records have been selected with similar conditions including all within site soil classification D ($180_{m/s}<V_{s30}<360_{m/s}$), magnitude between 6 and 8 Richter, and eruption depth less than 10km. These conditions are selected according to recommendations by (Oyarzo-Vera et al. 2012) for Wellington. These records are then scaled via the three main scaling method of amplitude scaling (NZS1170.5), spectral matching, and mean spectrum matching as described in section 1.1. DTHA analyses are carried out for each scaling method suit (14 records). As a means of highlighting the output, results are presented as the average of each suit together with the standard deviation, in order to examine the impact of each scaling method on the response of structures. Standard deviations are added to the average primarily to account for variability, enhance interpretation, and in the case of NBC2020, the addition is required as part of the compliance process. No study has been conducted to examine the dynamic response of rocking walls in relation to different scaling methods of ground motions.



(a)

(b)

(c)

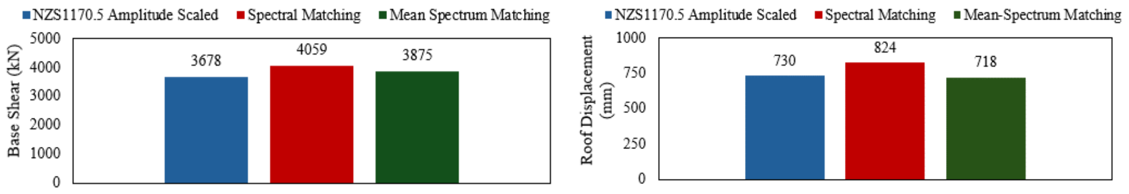
Figure 3. Scaled ground motions via method: (a) amplitude scaling. (b) mean-spectrum matching. (c) spectral matching.

2.3 Ground motion selection

In practice, it is best to carry out site-specific investigation, taking into account the soil-structure interaction and the characteristics of seismic waves as they impact the given location. Often, this step is not carried out or skipped due to cost or design and construction time constraints. It has never been studied how different ground motions originating from different tectonic sources affect rocking walls response. The results of this study can assist engineers in selecting ground motions based on the rocking wall system selected and the anticipated seismic zonation (Burlotos et al. 2022; Oyarzo-Vera et al. 2012) and allocating proportionate sources of ground motion for the structure for the purpose DTHA. For this purpose, 14 records for each tectonic ground motion source are selected which fit the best within the scaling criteria prescribed by NZS1170 and described in section above. The records are then amplitude scaled (NZS1170.5 method) to preserve the characteristics of the records. DTHA analyses are carried out for each tectonic source suit and results are presented as the average of each suit together with the standard deviation in order to compare them with one another and investigate the impact of each tectonic source on the response of structure.

3 RESULTS AND DISCUSSION

DTHA results indicate that the spectral matching results in the highest base shear and drifts (Figure 4). Although this is not entirely unexpected, perhaps it was anticipated that the acceleration hikes associated with amplitude scaling and mean-spectrum matching would result in large spikes in storey shear and displacement demands. Nevertheless, a structure that is sensitive to higher mode effects can be triggered more and put under more stress if accelerations are consistently present within a scaled period range (which corresponds to the structure) very close to the target spectrum, instead of pulses or abrupt increases and decreases in excitation. This can be more apparent with rocking walls that have friction hold-downs due to their elongated period after the slip force of the system and hold-downs. The consistency of spectral matched records has triggered both mode 1 and mode 2 a great deal, which govern the displacement behavior and the storey shear behavior of the structure respectively. The spectral matching method is therefore more conservative than the other two scaling methods, but it may be overly conservative if the design is penalized by codal requirements, such as the requirement to meet 10% above the spectrum as prescribed in ASCE7-22. It is more forgiving to select records using spectral matching, but it requires greater computational effort. Some records may require up to 100 iterations to meet the criteria for misfit limits set by user, resulting in practically an entirely new excitation record. While mean spectrum matching falls behind spectral matching, it still requires some computational effort and is an iterative process but allows the user to determine how much of the record to modify while still retaining some of the original characteristics. The results indicate that the standard deviations for spectral matching and mean spectrum matching are quite similar. Additionally, mean spectrum matching enables users to examine and observe how the structure responds to pulses and peak input accelerations, and it should not be penalized by codal requirements. The amplitude scaling method has provided the lowest base shear compared to all three methods, but it has predicted the displacement better than mean spectrum matching, but below spectral matching. DHTA with amplitude scaling often results in one or two records being discarded as having really unreasonable outputs. It requires rigorous selection and criteria to find 'good fit' records, whether to meet codal requirements or to achieve design objectives, such as limiting the k_1 factor or reaching target peak ground acceleration.



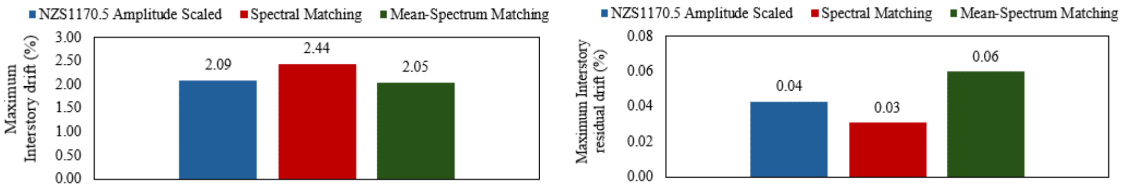
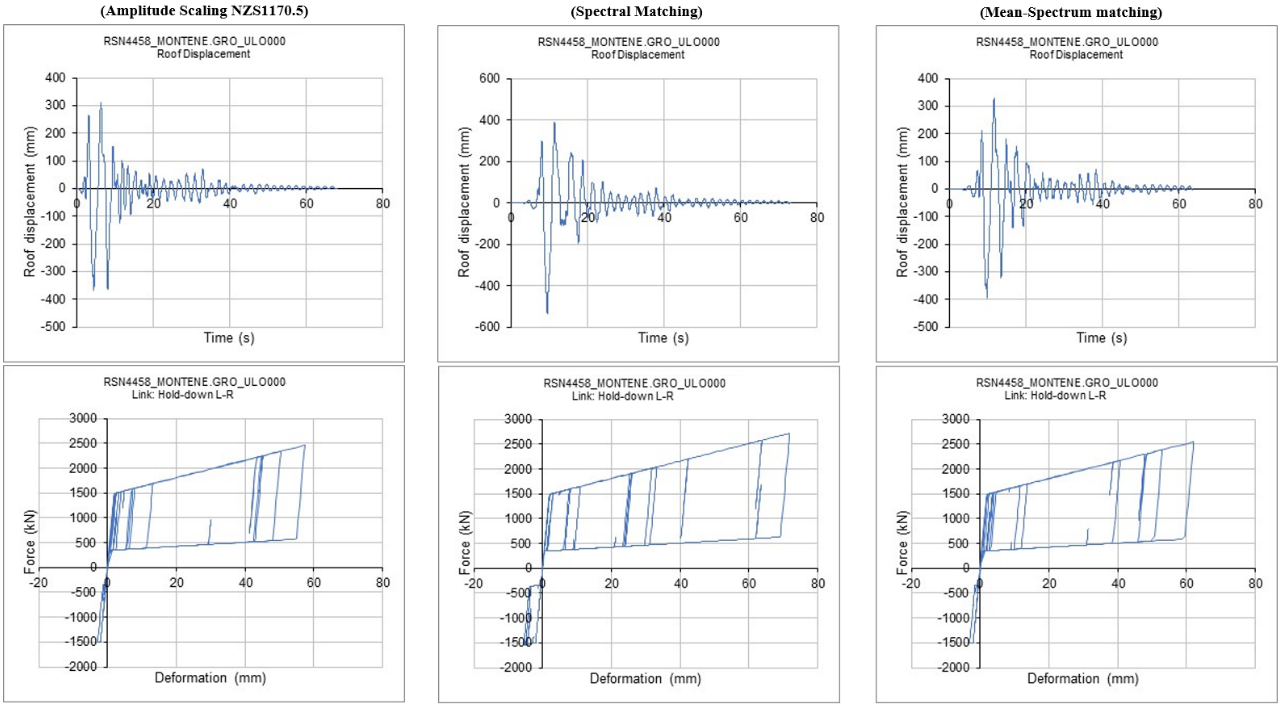


Figure 4. DTHA output as mean plus the standard deviation for base shear, maximum roof displacement, maximum interstorey drift, and maximum interstorey residual drift.

Figure 5 illustrates the performance comparison between the flag-shaped friction hold-down and the top displacements across three scaling methods. It demonstrates that amplitude scaling reflects the realistic displacement characteristics of the structure and hold-down for the particular ground motion record. For mean spectrum matching, the behavior and characteristics remain broadly consistent, with only an increase in demand observed. Conversely, spectral matching reveals noticeable alterations in the displacement profiles of both the structure and hold-down, with a notably greater increase in demand. Nonetheless, the flag-shaped friction hold-down has provided complete self-centering for the rocking wall structure.



(a) (b) (c)

Figure 5. Performance variations between the flag-shaped friction hold-down and top displacements under three different ground motion scaling methods for RSN4458 (a) amplitude scaling. (b) spectral matching. (c) mean-spectrum matching.

It is found that the intraslab ground motions have significantly higher base shear demand compared to subduction interface and shallow crustal record (Figure 6). As compared with subduction interface and shallow crustal records, intraslab ground motions exhibit significantly higher base shear demands. This is due to the very long duration of high frequency vibration, and it is observed that within this long vibration, the structure mainly transitions between modes 2 and 3 and occasionally enters the first mode. This is further confirmed with the roof and storey drift outputs from intraslab ground motions which have resulted in the least among others. This is evident from modes 2 and 3, which are the storey shear dominant modes, prevail over mode 1, which is the displacement dominant mode. The peak ground floor accelerations (Figure 7) also reveal the same pattern, indicating that scaling methods have generally similar profiles and that results are fairly comparable. By selecting ground motion records that fit well with the spectrum and the codal criteria, and by using good engineering judgment and scaling procedures, all three scaling methods should be valid and provide adequate results to be used for design. On the other hand, if a subduction intraslab source exists within the zone of the structure, special consideration should be given and at least one third of the records selected for DTHA should be selected from subduction intraslab ground motion source.

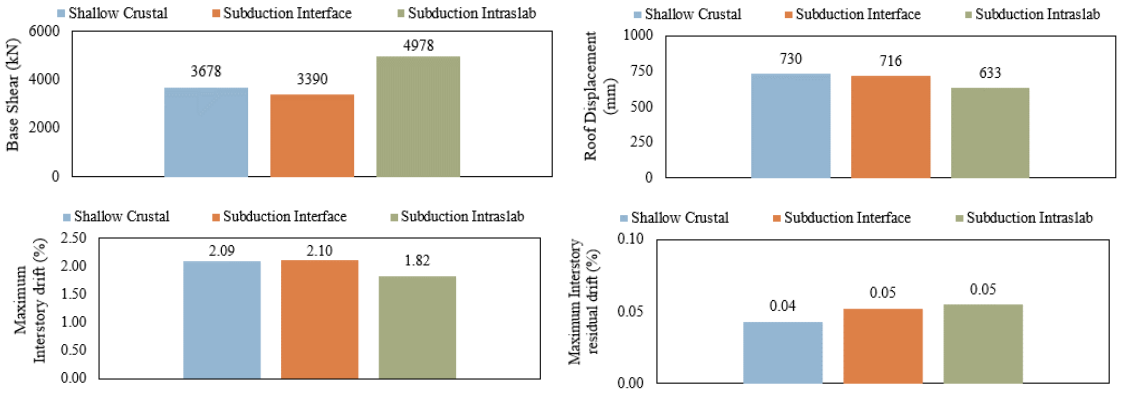


Figure 6. DTHA output as mean plus the standard deviation for base shear, maximum roof displacement, maximum interstorey drift, and maximum interstorey residual drift.

It may not be sufficient to choose ground motions based solely on how well they match the response spectrum, because this approach only indicates the highest response and does not indicate the anticipated number of cycles that may affect residual drifts. This detail is crucial, especially when using friction connections. This is of a less concern when flag-shaped friction hold-downs are implemented, and as shown in Figure 4 and 5, the structure for all scaling methods and ground motions is fully self-centred. If, however, subduction intraslab or interface faults are present in the zone, it is advised that half of the selected ground motions be chosen from subduction sources because of their characteristic long period of vibration.

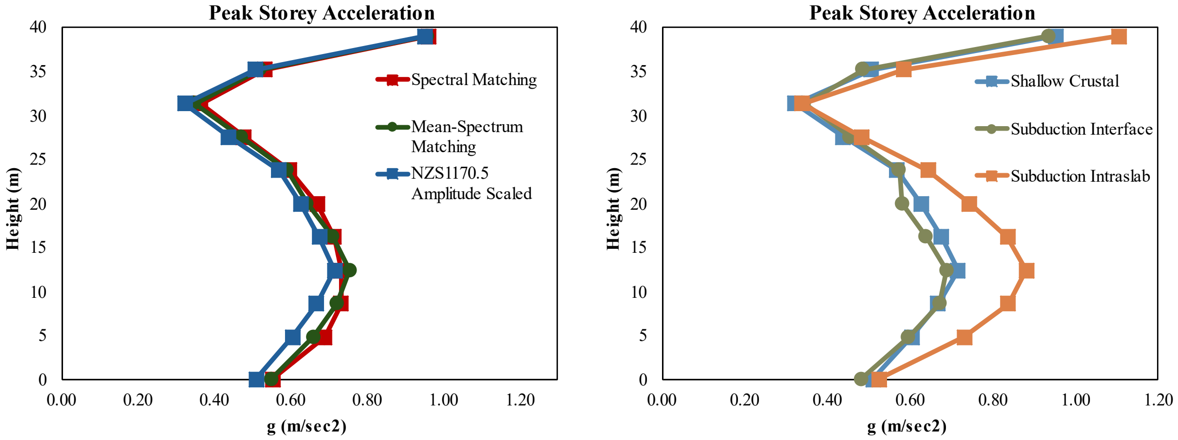
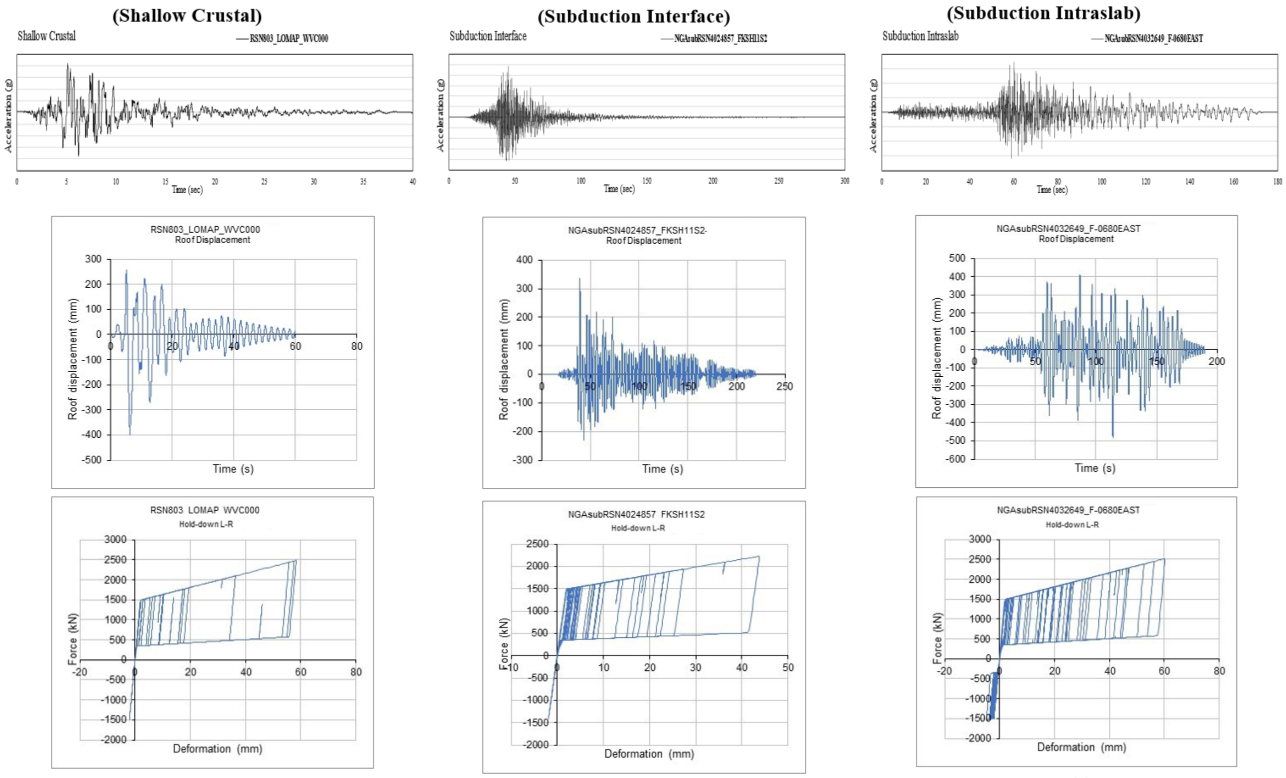


Figure 7. Peak floor acceleration: (left) ground motion records scaled for three main scaling methods (right) records from three main tectonic source.

Figure 8 presents a distinct example of each ground motion tectonic source, along with their respective structural displacement responses and flag-shaped friction hold-down performance. The variations in ground motion inputs, including duration of vibration, pulses, and characteristics are evident. These differences markedly influence the structural displacement response and the performance of the flag-shaped friction hold-down, as clearly depicted in the figure. Despite the varied input characteristics, the flag-shaped friction hold-down has consistently provided self-centering behavior for the structure. This outcome is achievable only when the friction hold-down exhibits repeatable and pinching-free hysteresis behavior. The findings also highlight the necessity of subjecting such hold-downs to rigorous testing regimes, like those outlined in ASCE7-22, to verify their ability to withstand intense, prolonged, and highly cyclic pulsed ground excitations typical of subduction tectonic sources.



(a) (b) (c)

Figure 8. A distinct example of each ground motion tectonic source, along with their respective structural displacement responses and flag-shaped friction hold-down performance (a) shallow crustal ground motion RSN803 (b) subduction interface ground motion NGAsubRSN4024857 (c) subduction intraslab ground motion NGAsubRSN4032649.

It is observed that the Hilber-Hughes-Taylor ‘alpha’ method of integration, though noticeably helps with convergence and speed of DTHA analysis, can produces significant energy errors. This method consists of a single parameter alpha, α, and is used to introduce numerical damping into the system, helping to control the amount of high-frequency response in the analysis, and can range from zero to -0.33. It is observed, however, that for any alpha value smaller than -0.1, there would be a significant increase in the energy error in the system, which would lead to an invalidation of the results. In cases where the structure is sensitive to higher mode effects, such as tall rocking walls, it is strongly recommended that the alpha value be set to zero. The alpha value of 0 effectively transforms the integration system into Newmark integration system, which is particularly stable and does not produce any energy imbalance.

4 CONCLUSION

Selecting ground motion records that fit well with the target spectrum and code requirements, along with applying sound engineering judgment and scaling techniques, ensures that all three scaling methods are reliable and produce results suitable for design purposes. It is however important to pay extra attention if the structure is located in a zone that contains a subduction intraslab source. In such cases, at least one third of the records used for dynamic time history analysis (DTHA) must be generated by subduction intraslab ground motion sources. It is recommended that if both subduction intraslab and interface faults are present in the zone, half of the selected ground motions be taken from subduction sources to account for the long duration of vibration resulting in a high number of cycles. According to the numerical simulation, the Hilber-Hughes-Taylor method using alpha values other than 0 is not suitable for tall rocking wall structures prone to higher mode effects as it introduces imbalanced energy into the system.

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