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EFFECTS OF INPUT MOTIONS FROM DIFFERENT TECTONIC SETTINGS ON SEISMIC SLOPE STABILITY ANALYSES

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Abstract

Seismic slope stability analyses are crucial for assessing the seismic performance of earthen structures and natural slopes. Input ground motions are often important components of such analyses and represent one of the main sources of variability in site response. Most studies on seismic stability analyses have been conducted using shallow crustal earthquake motions. However, differences in tectonic regimes can cause discrepancies in the frequency and duration contents of a recorded motion, and shallow crustal earthquakes alone cannot describe the seismic hazard in subduction-zone regions. This study aims to investigate the effects of different types of seismicity (namely shallow crustal, subduction intraslab, and subduction interface events) on seismic slope displacement. Analyses are performed at a site in Seattle, Washington, which is in an active tectonic region with seismic hazards from diverse earthquake sources. To determine the slope displacements, this study implements Newmark's method, which models a landslide as a rigid block that slides on an inclined plane. To represent different seismic sources associated with subduction zones, the conditional spectrum (CS) is used as the target spectrum for input motion selection. Hazard-consistent motions are selected to match the CS from appropriate ground motion databases. The permanent sliding block displacements are computed for different critical acceleration values. Considering the limitations of rigid block analyses, linear elastic coupled analyses are also performed. The findings of this study show that the consideration of subduction zone earthquakes significantly increases predicted slope displacements at the selected site compared to shallow crustal earthquakes, and thus, suggest that recordings from subduction zone earthquakes should be explicitly incorporated into seismic slope stability analyses in appropriate regions.

Keywords: seismic slope stability, subduction zone earthquake, strong ground motions, seismic hazards

1. Introduction

Seismic slope stability analyses are crucial for assessing the seismic performance of earthen structures and natural slopes. Input ground motions are important components of such analyses and represent one of the main sources of variability on the resulting slope displacements. Many studies to date have focused on investigating ground motion intensity measures that control slope displacements under seismic loading, such as peak ground acceleration, peak ground velocity, and Arias Intensity [1] [2]. However, the effect of ground motions from different tectonic settings has received limited attention because most studies have used shallow crustal motions as input to their seismic slope stability assessments [3] [4]. Recently, Bray et al. 2018 [5] proposed a simplified model for approximating earthquake-induced slope displacements for subduction interface events.

Ground motions from different tectonic settings have different amplitude, frequency content, and duration characteristics. This study evaluates potential discrepancies in slope displacement estimates stemming from the selection of ground motions from different tectonic settings. This can be particularly relevant for subduction regions where shallow crustal ground motions alone can not describe the hazard at the site. Simplified seismic slope displacement analyses, such as rigid block analyses and linear elastic coupled analyses, are useful for this purpose because they are commonly used in practice, and they can provide insights on the effects from input motion selection based on preliminary estimates of slope displacement for a wide range of conditions. We conduct rigid block analyses and coupled analyses at a site in Seattle, Washington, using ground motions compatible with the diverse seismic hazards in the region.

2. Study Site

Seattle, Washington, was selected as the study site because of its significant seismic hazards associated with distinct types of earthquakes. The hazard contributions at this site are from earthquakes associated with nearby crustal faults and the Cascadia subduction zone located off the Pacific Northwest coast. The subduction zone events can be further characterized as shallow large-magnitude interface earthquakes and deeper intraslab earthquakes. Therefore, the contributions to the seismic hazard in Seattle come from three distinct types of seismic sources. Seismic hazard deaggregation from probabilistic seismic hazard analysis (PSHA) is useful in separating the contributions to the hazard from different seismic sources. Deaggregation results for Seattle at a period of 0.01 s are presented in Fig. 1. The shallow crustal earthquakes are from faults within the North American plate (e.g., the Seattle Fault), within distances of 30 km. The intraslab earthquakes originate along the subducting oceanic plate at distances of 50 to 100 km. Lastly, the interface earthquakes occur between the North American continental plate and the Juan de Fuca oceanic plate at distances of 75 to 200 km.

We assume an idealized slope in Seattle and conduct seismic slope stability analyses consistent with the seismic hazards in that region. The characteristics of the assumed slope include: a height of sliding mass of 5 m, and a shear wave velocity (V_s) of the sliding mass of 560 m/s (representing dense soil; Site Class C of the National Earthquake Hazards Reduction Program [NEHRP] guidelines [6]. The V_s value assumed for the material below the sliding mass is 760 m/s to represent reference rock conditions in Seattle, WA (NEHRP Site Class B/C), and to facilitate the comparisons between displacements obtained from the sliding rigid block method and the elastic coupled analyses. Usually the rigid block analyses provide satisfactory results for thinner landslides on stiffer sliding masses [7]. Whilst the sliding rigid block method does not require geometric or stiffness characteristics of the sliding mass, the elastic coupled analyses do require such information. Moreover, because the focus of this paper is on the influence of hazard-consistent input motion selection on observed variability in slope displacements, the aforementioned slope characteristics are only selected as a reference, and are not meant to describe site-specific conditions.

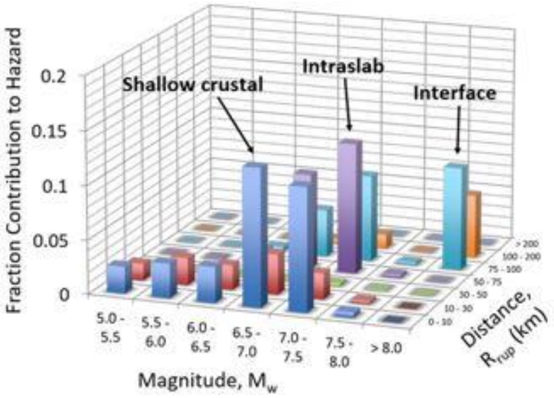

Fig. 1 – PSHA deaggregation results for Seattle at a period of 0.01 s [8]

3. Methodology

3.1 Target Spectra

The conditional spectrum (CS) [9] [10] is used as the target spectrum in this study due to its unique ability to consider the effects from each of the three types of seismic sources separately. The conditional mean spectrum is conditioned on a specific period of interest to have the same spectral acceleration as the uniform hazard spectrum (UHS). The spectral accelerations at all other periods of the conditional mean spectrum are computed based on the spectral acceleration at the conditioning period, and an inter-period correlation structure. Conditional spectra do not only consider the mean but also the variance in spectral values. For simplified seismic slope stability analyses, peak ground acceleration (PGA) is the conditioning ground motion parameter. Sliding will initiate only if the PGA is greater than the critical acceleration of the slope. Therefore, the CS is computed at a conditioning period (T) of 0.01 s for shallow crustal, subduction intraslab, and subduction interface events separately (Fig. 2a), using corresponding ground motion prediction equations (GMPEs) for each type of earthquake. The CS allows for ground motions to be selected from shallow crustal, subduction intraslab, and subduction interface events separately, matching their corresponding target spectra.

3.2 Input Motion Selection

To represent each of the seismic sources, input motions were selected from appropriate databases. The Enhancement of Next Generation Attenuation Relationships for Western U.S. (NGA-West2) database [11] is used to select shallow crustal earthquake motions, and the Japanese Kiban-Kyoshin network (KiK-net) database [12] is used for subduction events. Three input motion suites, each having eleven pairs of ground motions, are used in this study. Only the two orthogonal horizontal components of the recorded motions are considered. The readers are referred to Chowdhury et al. 2020 [13] for the details on input motion selection. Table 1 presents the details of the selected suites, and Fig. 2b shows the selected motions matching the CS at T = 0.01 s and its corresponding variability for the shallow crustal earthquake scenario. We observe that the corresponding response spectra of the selected input motions have a very good agreement to the target spectrum, in terms of spectral shapes and amplitudes, with respect to the conditional mean spectrum and its associated variability.

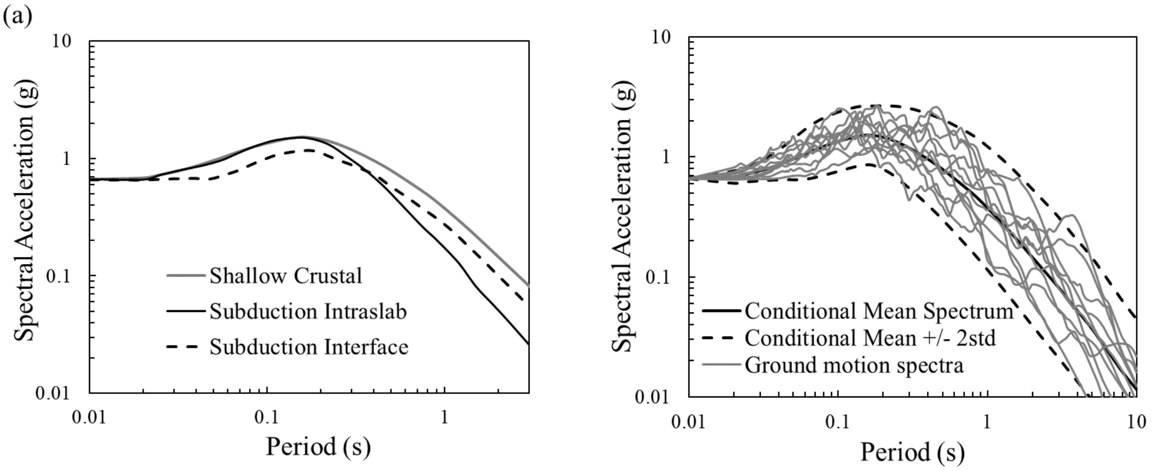

Fig. 2 – (a) Target conditional spectra with conditioning period T = 0.01 s, and (b) ground motion spectra of selected motions for the shallow crustal earthquake scenario. For greater readability, the corresponding standard deviations in Fig. 2a are not plotted.

Differences at intermediate and at longer spectral periods can be observed among the target spectra corresponding to each type of seismicity in Fig. 2a; not only they are associated with different tectonic regimes, but also to different earthquake causal parameters (see Table 1). At 0.01 s, all spectra converge at a PGA value of 0.66*g*. This behavior is expected, considering the calculation scheme for CS.

Table 1– Suites of selected ground motions

Suite No.	Target Spectrum	Conditioning Period (s)	Earthquake Scenario	Moment Magnitude (M_w)	Rupture Distance (km)	Database
i	CS	0.01	Shallow Crustal	7	5	NGA–West2
ii	CS	0.01	Subduction Intraslab	7	50	Kik-net (intraslab)
iii	CS	0.01	Subduction Interface	9	100	Kik-net (interface)

3.3 Slope Stability Analyses

In this study, the stability of a slope is assessed in terms of predicted permanent slope displacement using the software program SLAMMER [14]. To evaluate seismic slope stability, we performed (1) rigid block analyses, and (2) linear elastic coupled analyses. First, we used Newmark's method [15], which models a landslide as a rigid block that slides on an inclined plane. The block has a yield acceleration (a_y) for which the factor of safety of the slope is 1. When the PGA of a ground motion surpasses this yield acceleration, it results in a permanent displacement of the slope. In Newmark's method, once a ground motion record is selected, the portions of the record that exceed the critical acceleration are integrated twice to determine the permanent slope displacement. Due to the simplified nature of Newmark's method, it is initially used in this study to assess the differences in slope displacements for ground motions from different tectonic settings. Critical acceleration values of 0.05*g*, 0.1*g*, 0.15*g*, and 0.2*g* are used for all three selected suites of motions. Linear elastic coupled analyses are also performed for the same suites shown in Table 1. To allow for a legitimate comparison with results from the sliding rigid block method, a thin sliding mass and a stiff soil is selected for coupled analyses. Coupled analysis accounts for the flexibility of the soil mass and allows the dynamic response and the plastic displacement to be considered simultaneously [16]. Critical acceleration values of 0.05*g*, 0.1*g*, 0.15*g*, and 0.2*g* are again used for all three selected suites of motions.

4. Results and Discussion

4.1 Newmark's Rigid Block Analyses

Sliding displacements are calculated for the four selected yield acceleration values using each of the three selected suites of input motions. Fig. 3 presents the predicted slope displacements for the shallow crustal and subduction interface suites. Each point in this graph indicates the geometric mean of predicted sliding displacements from two horizontal components of a recorded ground motion. Despite the ground motions having the same PGA and similar spectral shapes within a suite, the predicted displacements in Fig. 3 display significant variability. The observed variability can be explained by the different ground motion characteristics (e.g., frequency content and duration). The median of predicted displacements from each suite at each yield acceleration is plotted in Fig. 4, along with the corresponding standard deviation in natural logarithmic space ($\sigma_{\ln D}$). The displacements from the two subduction suites are higher than the displacements from the shallow crustal suite, with the subduction interface suite having the highest values. For the standard deviation, in contrast, the crustal suite shows the highest values for most of the yield accelerations considered.

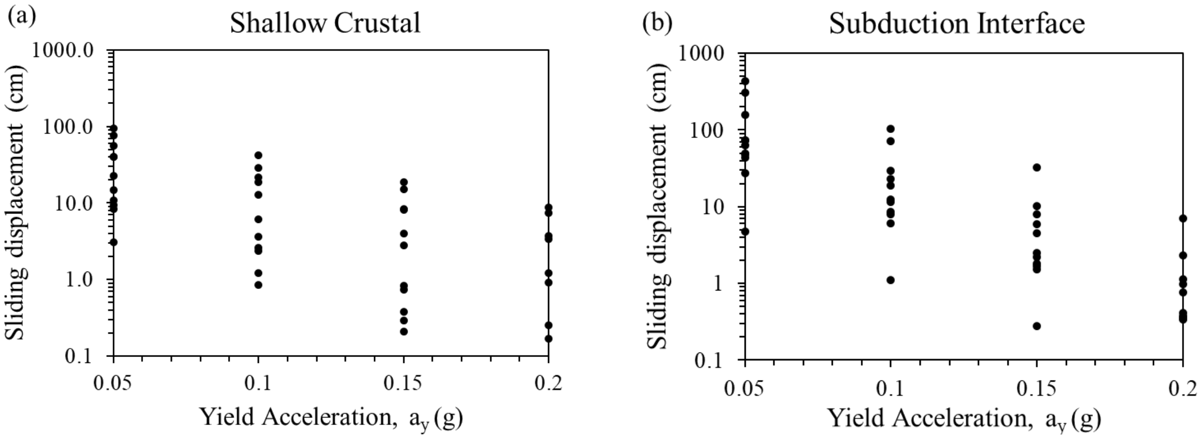

Fig. 3 – Estimated geometric means of slope displacements for the CS 0.01 s (a) shallow crustal suite, and (b) subduction interface motion suite.

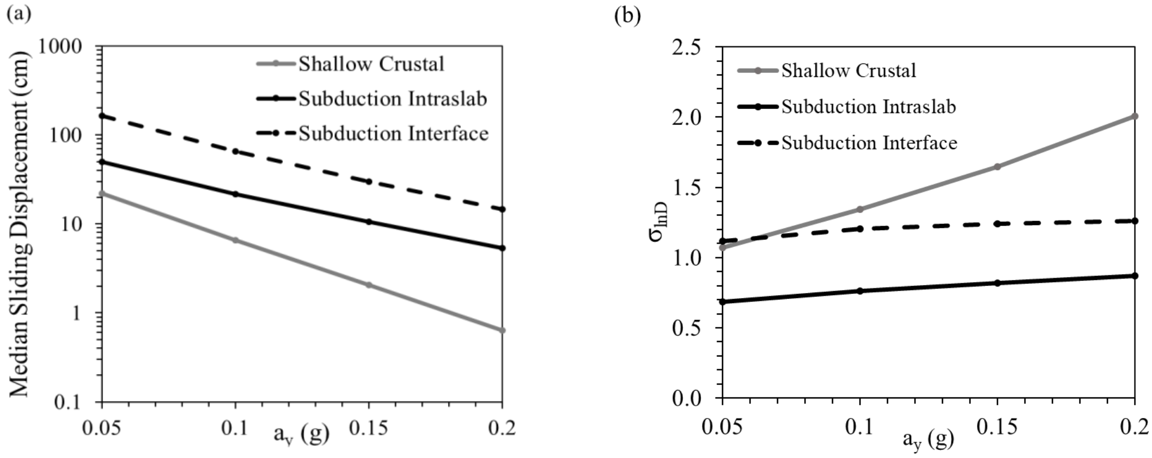

Fig. 4 – (a) Median displacement and (b) standard deviation of the predicted displacement for Newmark's rigid block analyses

Newmark rigid block analyses calculate the slope displacements by integrating the part of the time series that exceeds the critical acceleration twice; once from acceleration to velocity, and then again from velocity to displacement, as seen in the series of integrations. The accelerations in a time series can exceed the critical acceleration multiple times, and the cumulative displacements will add up to determine the total permanent displacement. Thus, slope displacement depends not only on the amplitude of the motion, but also on the frequency content and duration. To further investigate the underlying cause of the observed trends in Fig. 4, we plot the time series of a shallow crustal motion and a subduction interface motion in Fig. 5 along with the corresponding fourier amplitude spectrum. The significant duration ($D_{5\text{-}95}$) of the motions are also shown beside the time series. Despite having the same PGA, these two time series are significantly different in frequency content and duration. The time series from the subduction earthquake motions reach higher acceleration values over a longer duration of time, and thus, result in larger slope displacements.

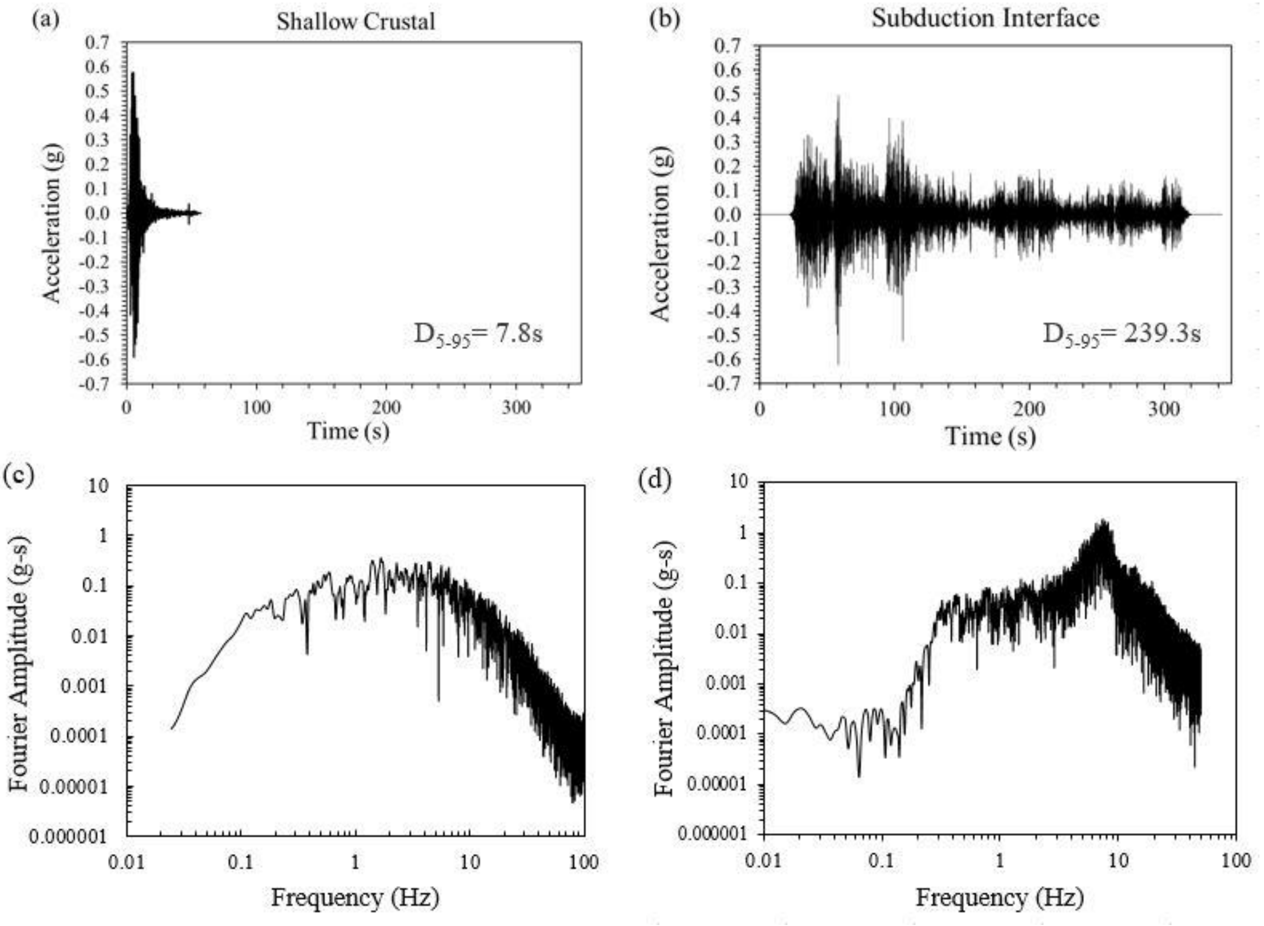

Fig. 5 – (a) & (b) Time series and (c) & (d) fourier amplitude spectrum of a shallow crustal and a subduction interface motion scaled to the same PGA value of 0.66*g*

4.2 Limitation of Newmark's method

Though Newmark's method enables a direct comparison of the effects of ground motions from different tectonic settings, it has several limitations for slope stability assessment. It considers the sliding mass as rigid with no internal deformation, while the soil mass is actually deformable. Moreover, Newmark's method does not consider the dynamic response of earth structures. Hence, Maksidi and Seed [17] proposed decoupled analyses, based on the work of Seed and Martin [18]. The analysis performs the dynamic response computation considering a deformable mass and then uses Newmark's double integration method to determine the plastic displacement. The decoupled approach also has limitations, as it ignores the simultaneous sliding while calculating the dynamic response. Thus, coupled analyses were developed [15] to account for the dynamic response and the plastic displacement simultaneously. Therefore, we also perform coupled analyses in this study to further investigate the observed trends in rigid block analyses.

Fig. 6 presents the results from coupled analyses for the same four yield accelerations previously selected. The coupled displacement graphs display similar trends to the ones observed from the rigid block displacement graphs. Subduction interface motions and subduction intraslab motions consistently predict higher slope displacement values than the shallow crustal motions. This difference can significantly impact the design of new slopes under seismic loadings, as well as the assessment of existing slopes during post-earthquake recovery efforts.

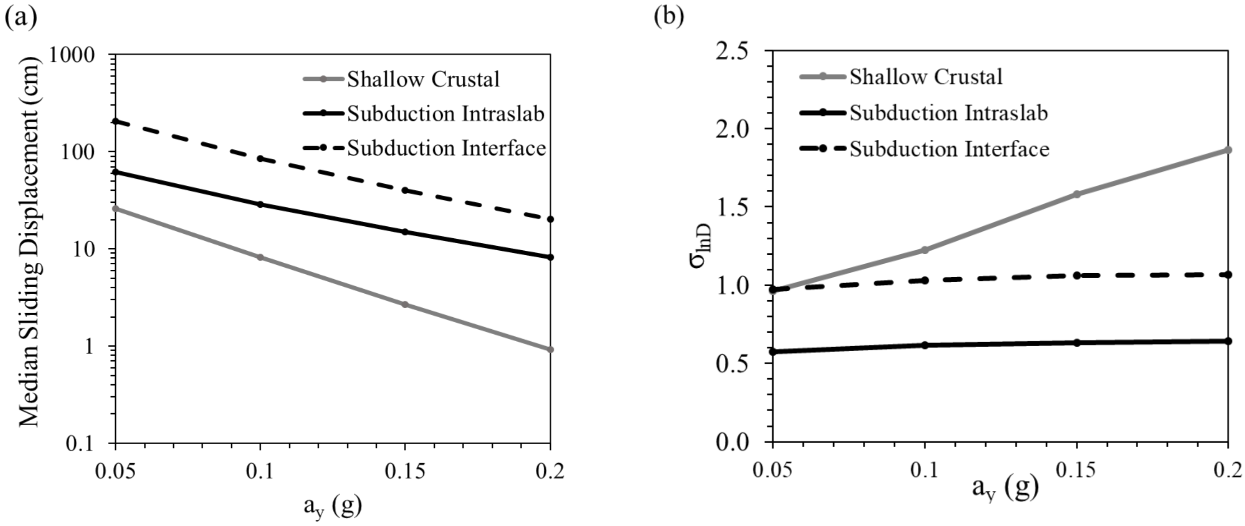

Fig. 6 – (a) Median displacement and (b) standard deviation of the predicted displacement for coupled analyses

The results from rigid block analyses and coupled analyses agree and evidence the importance of considering the ground motions from different tectonic settings separately, particularly in subduction zone regions. Despite having the same PGA, the suites of motion from three different tectonic regimes (crustal, subduction intraslab, and subduction interface) have shown different predictions for slope displacement. This demonstrates the significant impact that the tectonic setting has on ground motion characteristics, which eventually leads to differences in slope displacement. Therefore, it is imperative to consider ground motions from different tectonic settings separately. For a site like Seattle, where the hazard is dominated by subduction events, the exclusion of subduction motions from seismic slope stability analyses can lead to an underprediction of slope displacements.

6. Conclusions

This study compared predicted slope displacements for ground motions from different tectonic settings. The ground motions were selected from appropriate databases based on target spectra (conditional spectra) which were defined separately for three different earthquake scenarios (namely, crustal, subduction intraslab and subduction interface). Slope displacement analyses were completed using rigid block analyses and coupled analyses. Subduction zone ground motions showed significantly higher slope displacements compared to shallow crustal ground motions. The difference was as high as ten to twenty times for the selected critical acceleration values. The longer duration of the subduction motions, along with differences in the frequency content, contribute to these higher slope displacements. The results of this study suggest that ground motions from subduction earthquakes should be explicitly incorporated into seismic slope stability analyses in regions influenced by subduction zones. Otherwise, one may underestimate the hazard at these sites. Observing the significance of ground motion duration in slope stability estimates, future studies will focus on investigating its effect explicitly.

7. Acknowledgments

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