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Investigation of shear wave velocity depth variability, site classification, and liquefaction vulnerability identification using a near-surface V_s model of Christchurch, New Zealand

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ABSTRACT

Following the companion work of McGann et al. [1], several applications of a regional surficial shear wave velocity (V_s) model developed for Christchurch, New Zealand are examined. Comparisons of time-averaged V_s over various profile depths are used to characterize the inherent depth variability of the soils in the region. The degree of correlation between 30 m shear wave velocity (V_{s30}) and average velocity over shallower profile depths (V_{sz}) exhibited by the current model is compared to similar correlations developed for other locations, and consideration is given to differences between the four primary surficial geologic units present in the majority of the Christchurch urban area. The effects of the observed V_s depth variability on expected seismic response are assessed through the consideration of transfer functions developed for 30 m typical V_s profiles for eight subregions of Christchurch. The regional V_s model is also used to develop site classification maps for Christchurch using current New Zealand and international site classification schemes, and these maps are used to comment on the applicability of these conventional schemes to the soil profiles typical to the region. Models of 5 m shear wave velocity (V_{s5}) filtered by average soil behaviour type index are used to examine the relationship between V_{s5} and observations of liquefaction-related surface damage made following the 22 February 2011 Christchurch earthquake. It is shown that when properly filtered to remove regions with soils that are less susceptible (or not susceptible) to liquefaction due to soil composition, there is a good correlation between V_{s5} and severity of liquefaction-related damage.

1. Introduction

The 4 September 2010 M_w 7.1 Darfield and 22 February 2011 M_w6.2 Christchurch earthquakes resulted in strong ground motions throughout the greater Christchurch urban area [2,3]. The Darfield earthquake occurred about 15 km west of central Christchurch city, and resulted in moderate damage to local infrastructure and widespread liquefaction [4,5], while the Christchurch earthquake occurred approximately 4 km southwest of the city center, and the high-frequency amplitudes of the resulting ground motions across most of the city were much larger than in the Darfield event [2,3]. Liquefaction and lateral spreading associated with the Christchurch earthquake were significantly more severe and widespread than was observed the previous September, and accounted for the majority of the severe damage to properties and infrastructure [6–9].

The significant spatial variability of surficial ground motions recorded from these two strong earthquakes, among others, illustrates the importance of local site effects (seismic response of surficial soils) on surface ground motion and the importance of site-specific response analysis. The response spectra for the Darfield and Christchurch events were similar at multiple Christchurch strong motion stations despite the clear differences in source and path effects [10,11], though this was not observed at all stations. For example, several strong motion stations were located in areas where liquefaction was prevalent during the 22 February event, but not observed in the 10 September earthquake. The increased amplitudes characteristic of the Christchurch earthquake resulted in larger shear deformation and associated excess pore pressure build-up compared to the Darfield event, and the occurrence of liquefaction-related phenomena was correspondingly more significant and widespread. The resulting differences in the recorded ground motions at these stations provide further evidence for the importance of site-specific analysis [10], and further support the need for a detailed characterization of the spatial and depth variability

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of soils in the near-surface (depth <30 m) zone, particularly over the range of depths where liquefaction-related phenomena most often occur.

Design and building codes in New Zealand and internationally typically provide a site classification system with which to group soil deposits with continuously-varying, and often highly variable, strength and stiffness properties into a series of discrete categories. Such site classification systems inherently assume that it is acceptable for design purposes to account for local site effects in an approximate manner in lieu of site-specific characterization, and each site class provides distinct seismic design considerations based on the general expected soil response represented by the chosen classification system to be used as guidance in the design of structures. Travel time-averaged shear wave velocity to 30 m depth (V_{s30}) is the primary site classification metric currently used internationally; in the United States via the National Earthquake Hazards Reduction Program (NEHRP) [12,13] site classes, and in Europe via Eurocode 8 [14]. In New Zealand, the seismic design specifications contained in NZS1170.5:2004 [15] prescribe site classification based primarily on the small-strain site period, taken as four times the estimated or measured travel time of shear waves from the surface to underlying rock, with the soil-to-rock transition defined by a compressive strength ≥1 MPa. While such discrete site classification systems tend to oversimplify the importance of local site effects and site-specific response analysis, they are valuable in the sense that they can give an overall picture of regional variability in expected seismic response.

In this paper, the near-surface V_s model of Christchurch, New Zealand developed using the methodology discussed by McGann et al. [1] is used to characterize and investigate the inherent subsurface variability of the region in several ways. Firstly, the variability in V_s with depth across the region is examined via comparison of time-averaged shear wave velocity for various profile depths (V_{sz}). In particular, the relationship between V_{s30} and V_{sz} values for profile depths $z < 30$ m for the Christchurch soils is compared to similar relationships observed for sites in California [16], Japan [17], and Greece [18]. Secondly, transfer functions for typical 30 m V_s profiles at eight Christchurch subregions were computed to characterize the variation in expected small-strain seismic response due to the inherent depth variability. Site classification maps were also developed for the region using the site classification schemes prescribed by NZS1170.5:2004 [15] and NEHRP [12,13]. Thirdly, a regional model of 5 m time-averaged shear wave velocity (V_{s5}) is compared to the liquefaction-induced land damage map of van Ballegooy et al. [9] in order to determine if trends in the V_{s5} models correspond to the observed regional liquefaction vulnerability.

2. Regional V_{sz} models

Models of V_{sz} for z=5, 10, 20, and 30 m were developed over the Christchurch region using the procedure discussed by McGann et al. [1]. The regional V_{sz} models developed for the different target profile depths are useful for different purposes, with no one single model providing the means with which to fully characterize the expected seismic response of a particular site. The models for the shallower target depths, for example the regional V_{s5} (shown in Fig. 1) and V_{s10} (not shown here) models, can be used to provide a provide a characterization of the very-near-surface soils that can be useful in describing the regional distribution of soft and stiff soils within this zone. The models for the deeper target depths, in particular the V_{s30} model shown in Fig. 2 (reproduced from [1]), provide an indication of how a site may respond in an overall sense during earthquake shaking and how this expected overall response varies across the greater Christchurch area. The full set of regional models created for 5, 10, 20, and 30 m profile depths are available in McGann et al. [19] along with associated maps showing the distributions of V_{sz} at the CPT sites used in the development of each model.

These models reveal the significant spatial variability in V_s for the region, and through comparison of the V_{s5} and V_{s30} models, indicate a similar variability with respect to depth. Some features present in the V_{s30} model correspond directly to theV_{s5} model, such as the increased velocities for the marine/dune sands near the Pacific coast and for the over-bank gravel lobes [20] to the west where the profiles are consistently more stiff on average than the surrounding areas. For regions where the V_{sz} models have relatively contrasting values, the surfaces shown in Figs. 1 and 2 provide some insights into the profile characteristics and expected seismic responses. Profiles located in areas with lower V_{s5} may be relatively soft on average over the full 30 m in comparison to the entire region (e.g. Sydenham and Papanui, near boxed regions 4 and 5, respectively), or may be relatively stiff on average (e.g. Kaiapoi and parts of Halswell) due to changes in the soil profile occurring below 5 m depth.

2.1. Assessment of shear wave velocity depth variation

The degree of correlation between the various V_{sz} models is assessed by comparing the V_{s30} values at the grid points of the regional model with the corresponding V_{sz} values for profile depths $z < 30$ m. These comparisons are made separately for the grid points located in each of the four primary surficial geological units (QMAP units) considered in this study: alluvium, marine/dune, estuarine, and peat/swamp (see McGann et al. [1] for further information). Fig. 3 presents the results of the comparisons, and Table 1 provides the coefficients of determination, r^2, and lognormal standard deviations, σ_ϵ, between V_{sz} and V_{s30} for the full dataset (all QMAP units) and the sites within each QMAP unit. As shown in Fig. 3, the degree of correlation between V_{sz} and V_{s30} differs depending on the QMAP units of the Christchurch sites. For sites in the alluvial, marine/dune, and estuarine QMAP units that comprise the majority of the overall dataset, there is little correlation between V_{s5} and V_{s30}, and the degree of correlation between V_{sz} and V_{s30} generally increases with profile depth. A much stronger correlation is observed for all profile depths in the peat/swamp sites, especially relative to the other QMAP units. This increased correlation is likely due to the soil profiles of the peat/swamp sites, which are often characterized by relatively thick layers of low V_s soils near the ground surface that substantially affect, and tend to homogenize, V_{sz} values due to their prominence in the profiles. The differences in the degree of correlation between V_{s30} and V_{sz} in terms of the surficial geologic units highlights the importance of consideration for the one prevalent soil type or layer (low or high V_s) that controls the 30 m velocity profile when computing V_{s30}. The scatter evident in the results of Fig. 3 and Table 1 indicates that the use of mean-value empirical equations for this purpose should be done with care, especially for shallow depths.

The lack of correspondence between V_{s30} and V_{sz} for shallow z in the non-peat/swamp sites observed in Fig. 3 is inferred as a result of the stratified nature of the soils underlying the Christchurch region. The upper boundary of the Riccarton Gravel that underlies most of the region is <30 m below the ground surface [1,20,21]. For a given site, the shear wave velocity of the Riccarton Gravel is both independent of, and much larger than, that in the overlying soils, therefore, V_{sz} values for depths above the Riccarton Gravel will not directly correspond to velocities averaged over the entire 30 m profile. The relationship between the depth to the Riccarton Gravel and the degree of correlation between V_{sz} and V_{s30} is evident in the spread in the data points for the alluvium and marine/dune sites in the V_{s5} and V_{s10} plots of Fig. 3. The sites that plot nearer the 1:1 correlation line are likely those sites where the Riccarton Gravel is deep (i.e. eastern areas), and the sites that plot nearer the left-hand edge of the plots are likely those where the Riccarton Gravel is shallow (i.e. western areas and those near the Port Hills to the south). In effect, for the alluvium and marine/dune sites, moving from left to right across the data points (for a given y-axis value) in the V_{s5} subplot of Fig. 3 represents a move from west to east across Christchurch.