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Applicability of existing empirical shear wave velocity correlations to seismic cone penetration test data in Christchurch New Zealand

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ABSTRACT

Seismic piezocone (SCPTu) data compiled from 86 sites in the greater Christchurch, New Zealand area are used to evaluate several existing empirical correlations for predicting shear wave velocity from cone penetration test (CPT) data. It is shown that all the considered prediction models are biased towards overestimation of the shear wave velocity of the Christchurch soil deposits, demonstrating the need for a Christchurch-specific shear wave velocity prediction model (McGann et al., 2014) [1]. It is hypothesized that the unique depositional environment of the considered soils and the potential loss of soil ageing effects brought about by the 2010–2011 Canterbury earthquake sequence are the primary source of the observed prediction bias.

1. Introduction

The small strain shear modulus is a fundamental soil property required for characterizing the seismic response of surficial soils as it defines the shear stress–strain response at low strain levels and is often used to define normalized models to describe the reduction of the soil shear modulus with increasing levels of strain. Due to this association with low strain levels, the small strain shear modulus is highly susceptible to disturbances caused by sampling and laboratory reconsolidation, therefore, it is difficult to directly measure and values of the small strain shear modulus are often obtained via measurements of the in situ shear wave velocity, V_s, which is fundamentally related to the small strain shear modulus through the elastic wave propagation equation [2].

There are numerous techniques available for obtaining in situ measurements of V_s, including crosshole, downhole, and uphole techniques [3,4]; active-source surface wave techniques such as spectral analysis of surface waves [5] and multichannel analysis of surface waves [6]; passive-source surface wave techniques such as linear [7,8] and microtremor array methods [9,10]; the seismic cone penetration test (SCPT) [11]; and suspension logging [12]. These direct measurement approaches all have specific advantages and disadvantages relative to each other, however, one drawback that is common to these methods in general is the need for specialized equipment and training. Due to these requirements, such measurements are not commonly made during site characterization efforts for projects of lower relative importance. As a result, there is often a lack of site-specific V_s data for such sites and a general scarcity of data for use in region-wide characterization efforts such as the development of regional ground shaking hazard maps.

Direct measurement of V_s is always preferable to indirect estimation, however, due to the noted difficulties with obtaining direct measurements for a particular site, or on the scale necessary for a region-wide characterization, correlations of V_s with soil data obtained from common site investigation techniques such as the standard penetration test (SPT) or cone penetration test (CPT) are useful. Many such correlations have been developed in the past based on various CPT-based predictor variables for various soil types from locations around the world [13–19]. Wair et al. [20] provide a good general overview of these previous CPT-based efforts as well as similar correlations developed using SPT resistance data as predictor variables.

A detailed characterization of the subsurface V_s profile for the greater Christchurch, New Zealand area, is an essential tool to aid in identifying and understanding the physical processes resulting in the strong ground motions observed in the 2010–2011 Canterbury earthquake sequence [21–26]. While in situ measurement of V_s is impractical on the scale necessary for a full characterization of the region, measurements made at selected sites can be used to

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establish a region-specific relationship between measured V_s and CPT data. When combined with the large existing local CPT data set [27], such a correlation can be used to produce the desired description of the near surface V_s profile of the Christchurch region [28]. In this paper, data obtained using SCPTu devices [11] at 86 sites located throughout the greater Christchurch area are used to establish the need for a Christchurch-specific CPT–V_s correlation through an assessment of the applicability of existing CPT–V_s models developed elsewhere to describing the strength-to-stiffness relationship for the soils and site conditions found in the Christchurch region. The compiled SCPTu database is first presented, including the spatial distribution of sites, data processing, and overall database statistics. Existing CPT–V_s correlations are then described and the prediction bias when applied to the SCPTu database is examined with respect to various predictor variables. Finally, the specific nature of the soils encountered and the recent Canterbury earthquakes are considered as possibilities for the observed bias in the considered prediction models.

2. Christchurch SCPTu database

Seismic piezocone (SCPTu) data were obtained at 86 sites in the greater Christchurch area and made available through the Canterbury Geotechnical Database [27]. Fig. 1 shows the locations of the SCPTu sites. Those sites closest to central Christchurch are in the main portion of Fig. 1; two sites located beyond the southern boundary of this main portion (in Tai Tapu), and 14 sites located beyond the northern boundary (five in Spencerville and nine in Kaiapoi) are shown in the insets on the right-hand side. As shown in Fig. 1, the majority of the Christchurch sites are located near the Avon River, though there are a number of sites near the Heathcote River or located away from either river system. The Spencerville sites are located along the Styx River and the Kaiapoi sites are near the banks of the Kaiapoi River and Courtenay Stream.

2.1. Geological setting of SCPTu sites

The inset at the left of Fig. 1 shows the centrally located SCPTu sites with respect to the surficial geologic units of the Christchurch urban area [29]. As shown, the surficial soils at these sites are split between the beach, estuarine, lagoonal, dune, and coastal swamp deposits of the Christchurch Formation (blue and grey-blue in Fig. 1 inset) and the fluvial channel and overbank sediment deposits of the Springston Formation (yellow and yellow-grey in Fig. 1 inset). The sites located in Tai Tapu, Spencerville, and Kaiapoi (as well as a site in southern Halswell) are located outside of the bounds of the surficial geologic survey map, and are therefore not included in this inset. These sites are however located within the same surficial geologic units. Of the 86 total SCPTu sites, there are 26 Christchurch Formation sites, 56 Springston Formation sites, and 4 sites located on the boundary of the two. The Christchurch and Springston Formations that exist on the surface of the Canterbury plains date to the Holocene period (deposited ≤ 10,000 years before present day). The content of the Springston Formation is primarily well-sorted, rounded gravel within a sand matrix with occasional silt and clay lenses. The Christchurch Formation is composed primarily of blue gravel, sand, shells, sandy silt, clay, peat, and wood [30]. The groundwater table ranged between 0.4 and 3.4 m depth at the SCPTu sites.

2.2. Data processing

Pseudo-interval travel time measurements were made by recording seismic signals at 2 m intervals at each SCPTu site. The horizontal distance between the source plank on the ground surface and the SCPTu rod was reported as 3.6 m in all considered cases. The 2 m sampling interval used in these tests is not ideal (an interval ≤ 0.5 m would be preferable), however, the SCPTu data were collected prior to this study and the sampling interval could not be controlled. Shear wave velocities were determined from the seismic signals using the cross-over method [11] for sites with only pre-processed wave data available (40 of 86 SCPTu), and the cross-correlation method [31] for sites with digitized data available (46 of 86 SCPTu). Fig. 2 shows an example of the polarized seismic wave traces that were used to determine V_s via the cross-over method, or to check the V_s returned by the cross-correlation method.

The V_s values determined from the available data are assumed to be constant over the full intervals between the measurements, and the midpoint of each interval is assumed to be the depth of the V_s data point. For comparison between the V_s and CPT data, the geometric mean of the CPT data are determined over the V_s measurement intervals (as the subsequently developed correlation is linear in V_s space), yielding 513 coupled pairs of V_s and CPT data. The use of the geometric mean in variable strata leads only to less precision, however, the variance is low for all cases and no data points were omitted due to excessive variability in the CPT data within the intervals. Averaging the CPT data in this manner helps to alleviate issues associated with comparing measured to CPT-correlated V_s values at locations where the smaller measurement intervals of the CPT (≈ 1–2 cm) detect a localized feature that

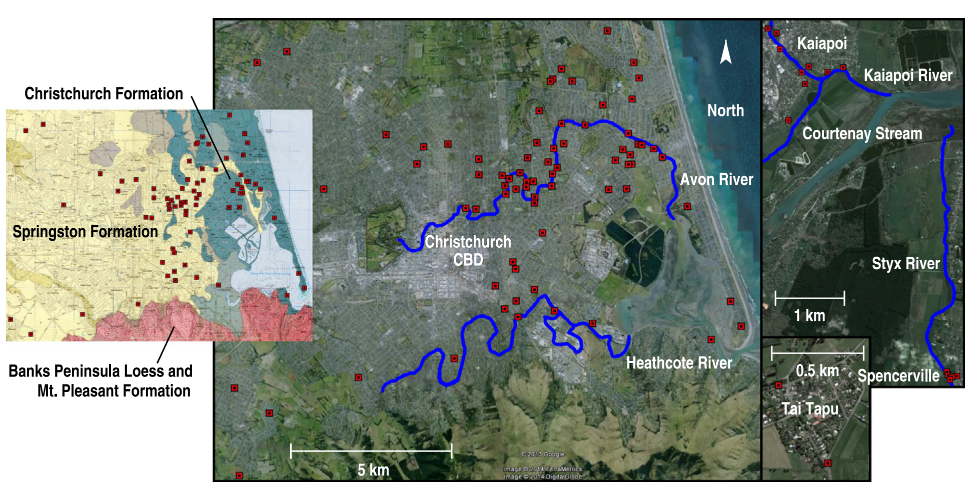

Fig. 1. Map of Christchurch showing the 86 SCPTu site locations (Kaiapoi, Spencerville, and Tai Tapu sites inset at right). The sites are shown in relation to surficial geologic deposits [29] in the inset at left. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)