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Development of an empirical correlation for predicting shear wave velocity of Christchurch soils from cone penetration test data

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A B S T R A C T

Following the companion study of McGann et al. [1], seismic piezocone (SCPTu) data compiled from sites in Christchurch, New Zealand area are used with multiple linear regression to develop a Christchurch-specific empirical correlation for use in predicting soil shear wave velocities, V_s, from cone penetration test (CPT) data. An appropriate regression functional form is selected through an evaluation of the residuals for regression models developed with the Christchurch SCPTu database using functional forms adopted by previous empirical correlations between V_s and CPT data. An examination of how the residuals for the chosen regression form vary with the predictor variables identifies the need for non-constant depth variance in the regression model. The performance of the model is assessed through comparisons of predicted and observed V_s profiles and through forward predictions with synthetic CPT data. The new CPT–V_s correlation provides a method to estimate V_s from CPT data that is specific to the non-gravel soils of the Christchurch region in their current state (caution should be used for western portions of the Springston Formation where SCPTu data were sparse). The correlation also enables the utilization of the large, high-density database of CPT logs ($>15,000$ as of 1/1/2014) in the Christchurch region for the development of both site-specific and region-wide models of surficial V_s for use in site characterization and site response analysis.

1. Introduction

Site effects related to the influence of near-surface (<50 m) stratigraphy strongly affect observed surficial ground motions. Seismic waves must always pass through these near-surface soil and rock layers before reaching the surface, thus site effects tend to be a systematic feature of observed ground motions at a particular location, while path and source effects, which also strongly affect surficial ground motions, can vary significantly for earthquakes originating from different sources. The systematic nature of site effects at a particular site, in combination with the ready availability of direct measurements and estimates of the characteristics and properties of the near-surface soils, indicates that local site effects can be modelled with potentially greater accuracy than source and path effects and, therefore, offer a potentially more efficient means with which to predict the character, and effects, of future surficial ground motions at specific locations [2–5].

The small strain shear modulus is a fundamental parameter required to evaluate the dynamic response of soil deposits using seismic site response analysis. It defines the shear stress–strain response for low levels of strain ($<10^{-4}$%), and is typically used to define normalized relationships describing the reduction in soil shear modulus with increasing levels of strain that is critical to nonlinear and equivalent linear site response analyses (e.g. [6,7]). The small strain shear modulus is highly susceptible to disturbances that are nearly unavoidable in any laboratory assessment [8], therefore, in situ measurements or estimates of shear wave velocity, V_s, which is related to the small strain shear modulus through the linear elastic wave propagation equation, are used to obtain the low strain soil shear modulus profiles necessary for dynamic site response analyses.

Near surface shear wave velocities can be directly estimated using surface wave measurement techniques such as the spectral and multi-channel analysis of surface waves techniques (SASW and MASW, respectively) [9,10], linear and microtremor array methods [11–14], as well as by techniques requiring one or more

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boreholes such as crosshole and downhole techniques [15,16] and P-S suspension logging measurements [17]. Near surface V_s profiles can also be obtained via empirical correlations with common geotechnical investigations such as the standard penetration test (SPT) (e.g. [18–21]) and the cone penetration test (CPT) (e.g. [19,21–27]). Such empirical correlations are typically developed through regression analysis using a series of predictor variables from the conventional geotechnical investigations (SPT or CPT) and V_s measurements obtained through one of the previously mentioned techniques. Many of the more recent empirical correlations have been developed using data for general soil deposits (i.e., cohesive and cohesionless) from globally located sites of varying geological ages in order to obtain prediction correlations that can be applied in a general manner.

Direct in situ V_s measurements are preferable to the indirect V_s estimations obtained from the application of empirical correlations, however, they have disadvantages that limit their use in general practice. Surface wave methods are useful in that they are generally non-intrusive, but they require the solution of an inverse problem, which is often ill-posed. As a result, V_s profiles estimated using surface wave techniques often have problems related to the non-uniqueness of the solution [28] and to the equivalence problem [11,29]. These issues can be manifested in the resulting profiles via decreased resolution with increasing depth, an inability to identify thin layers, and difficulties in resolving the portions of layers adjacent to large velocity contrasts [8]. Borehole-type measurement techniques are inherently invasive, though this in itself does not preclude their use, as invasive site characterization techniques (e.g. SPT and CPT) are common in practice. Compared to surface wave methods, borehole-type measurement techniques have greater capacity to resolve inclusions and anomalies that may be missed by surface-based approaches, but have increased temporal and financial expenses associated with drilling (especially for crosshole techniques, which require multiple boreholes) [8], and only represent the subsurface conditions at a single point, rather than the conditions averaged along a line. The downhole technique, of which the seismic cone penetration test (SCPT) is a specialized subset, requires only a single borehole, but can suffer from depth limits depending on the energy of the seismic wave source. The suspension logger test can be used for great depths (>100 m), and is arguably the most precise invasive measurement method currently available, but this test has limited application in soft sediments [8].

The noted difficulties associated with direct V_s measurement techniques, along with the expenses related to the specialized equipment and training associated with their use in practice, typically results in their use only at certain higher-importance sites and a corresponding scarcity of V_s data available for region-wide subsurface characterization. In contrast, site investigation techniques such as SPT and CPT are commonly applied to a broader scope of projects, and empirical correlations based on the data obtained by such tests can be used to provide the V_s data necessary for both region-wide and site-specific ground response assessments. This is especially true in Christchurch, where the extensive site investigations made following the 2010–2011 Canterbury earthquake sequence [2,30–34] have resulted in a large, high density database of CPT logs ($>15,000$ as of 1/1/2014) for sites located throughout Christchurch and the surrounding suburbs and towns.

This paper presents the development of an empirical correlation between CPT data and soil V_s. The paper extends on McGann et al. [1] who used a SCPTu database obtained from 86 sites in the greater Christchurch, New Zealand area to evaluate the suitability of four existing empirical models for estimating the in situ V_s of Christchurch soils from CPT data. The existing CPT–V_s correlations [22–24] were shown to be biased towards overestimating the observed V_s profiles on average, with the Andrus et al. [22] correlation providing the predictions with the least amount of prediction error. Reduction or loss of age effects was presented as one of the possible reasons for the observed overestimation bias in the existing correlations when applied to Christchurch soils, as the examined Christchurch sites do not display an increase in V_s with effective deposit age in line with that displayed by the existing Andrus et al. [22] data set. The observations discussed in McGann et al. [1] demonstrated the need for the development of a new Christchurch-specific CPT–V_s correlation through regression analysis, and this development is discussed in the current paper. Firstly, the development focuses on the selection of an appropriate functional form for the regression analysis. Secondly, the quality of the regression using the selected functional form is assessed, with particular attention given to the dependence of the model prediction and standard deviation on various predictor variables, and also direct comparison for selected profiles. The details of the correlation development are presented in the ensuing sections, followed by a discussion of the recommended Christchurch-specific CPT–V_s correlation determined through this process.

2. Evaluation of regression function forms

The first step in the development of a regression between CPT data and V_s is an assessment of potential functional forms. McGann et al. [1] examined the predictive capabilities of several existing CPT–V_s correlations to SCPTu data from the Christchurch region, and the functional forms of the those examined relationships form the basis of those considered herein. Specifically, six distinct relations between V_s and various CPT-based variables are considered as candidate regression functions. The considered regression forms include the Andrus et al. [22] form

$$V_s = a{q_t}^b{I_c}^d z^e \tag{1}$$

where a, b, d, and e are regression coefficients, q_t is the cone tip resistance corrected for pore pressures acting behind the cone tip [35], I_c is the soil behaviour type index [36], and z is the depth; the Hegazy and Mayne [23] form rearranged to solve for shear wave velocity

$$V_s = aQ_{tn}\exp(bI_c)\left(\frac{\sigma'_{v0}}{p_a}\right)^{0.25} \tag{2}$$

where Q_{tn} is the normalized cone resistance [36,37], σ'_{v0} is vertical effective stress, and p_a is atmospheric pressure; the Robertson [24] form

$$V_s = \left[10^{a+bI_c}\left(\frac{q_t-\sigma_{vo}}{p_a}\right)\right]^{0.5} \tag{3}$$

in which all terms are previously defined; the form recommended for use in CPT–V_s regression analysis by Wair et al. [21]

$$V_s = a{q_t}^b{f_s}\sigma'^{e}_{vo} \tag{4}$$

where f_s is the cone frictional resistance; and two additional hybrid forms that consider different combinations of terms from the forms in Eqs. (1) and (4) are

$$V_s = a{q_t}^b{f_s}^d z^e \tag{5}$$

$$V_s = a{q_t}^b{I_s}^d\sigma'^{e}_{vo} \tag{6}$$

Multiple linear regression in logarithmic space is used with the Christchurch SCPTu data set for each of the six considered regression forms. Fig. 1 shows a comparison between the measured V_s values from the database and the V_s values estimated using each considered regression form (indicated by equation number). The plots and associated coefficients of determination,