Soil Dynamics and Earthquake Engineering 31 (2011) 431–439

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Evaluating empirical regression equations for *Vs* and estimating *Vs*30 in northeastern Taiwan

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ARTICLE INFO

Article history:
Received 15 December 2009
Received in revised form
7 September 2010
Accepted 9 September 2010

ABSTRACT

The shear wave velocity of shallow sediments is very important in seismic wave amplification and thus *Vs*30 is a well-known parameter for site classification. Based on the relationship between *Vs* and soil indexes, the empirical regression equations were evaluated using more than 600 data sets from the Ilan area and the Taipei Basin. Multivariable analysis, which can increase the accuracy of regression equations, was used in this study. Three extrapolations were compared, and then the most accurate bottom-constant extrapolation was adopted to estimate *Vs*30 at 16 boreholes, none of which reached a depth of 30 m. Ultimately *Vs*30 was derived for 110 free-field strong motion stations, and the stations in northeastern Taiwan were reclassified according to the *Vs*30-based NEHRP provisions. Regression equations of *Vs* and the extrapolation of *Vs*30 were also applied to boreholes with only *N*-values and corresponding depths of less than 30 m for assessing the *Vs*30 and NEHRP class.

1. Introduction

It has been recognized that soft and young sediments covering firm bedrock can amplify seismic waves and cause severe damage during a large earthquake. Anderson et al. [1] noted that the strata in the top 30 m have a considerable influence on the character of the ground motions created. The NEHRP (see Table 1, the abbreviations and acronyms used in the present paper were tabulated as well as the original definitions) recommended *Vs*30 as a significant indicator for classifying sites in recent building codes [2,3]. The *Vs*30-based NEHRP Provision classes are shown in Table 2. Recently, Massa et al. [4] regarded site classification as a significant factor as well as magnitude and epicentral distance in the empirical strong-motion prediction equation. In addition, the NGA project [5,6] also suggested that the site conditions of recording stations are a significant parameter in strong ground motion prediction. It should be noted that strong motion records in Taiwan are also included in the PEER database.

Several researches recognized that *Vs* is correlated with soil indexes such as SPT-N (or N), depth, soil type, and geological epoch [7–9]. Adopting an approach akin to those mentioned above may be beneficial for the boreholes drilled previously, as they usually only have data pertaining to *N* and the corresponding depths, but without any measured *Vs*.

Since *Vs*30 is considered an important factor in ground motion prediction, assessing its value is essential. Seismic refraction, reflection, and SASW are all well-known noninvasive and active source techniques for estimating *Vs*. For example, Williams et al. [10] used high-resolution seismic refraction and reflection methods to derive *Vs* profiles as well as *Vs*30 in the St. Louis region. On the other hand, down-hole, up-hole, cross-hole, and suspension PS-logging are prevalent invasive and active source techniques. For example, Bang and Kim [11] used the SPT-up-hole method to determine *Vs* profiles to compare them with those determined by down-hole and SASW methods. Furthermore, passive source techniques such as the microtremor array method is also becoming popular [12,13]. Kuo et al. [13] estimated *Vs* profiles by three different techniques in shallow subsurface layers, and considered the suspension PS-logging as being able to observe precise P- and S-wave velocities in one-dimensional borehole measurements. Boore and Asten [14] compared shear-wave slowness profiles obtained by various invasive and noninvasive methods at several sites in the Santa Clara Valley. Ohta and Goto [15] proposed an in-situ down-hole technique for estimating *Vs* during a standard penetration test, and then combined it with other soil indexes to evaluate empirical regression equations.

Considering the fact that many boreholes drilled in the past did not reach 30 m, Boore [16] proposed an extrapolation using the correlation between *Vs*30 and the average *Vs* of other shallower depths. Boore and Joyner [17] and Huang et al. [18] were of the opinion that S-wave travel time increases with the depth in a

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doi:10.1016/j.soildyn.2010.09.012