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Importance of coherence between geophysical and geotechnical data in dynamic response analysis

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Abstract. The demand for a precise evaluation of shear wave velocity V_s, is gaining interest in the field of geotechnical engineering due to its importance as a key parameter required to properly evaluate typical characteristics of soils. Nowadays, V_s measurements are performed on the field using different methods, such as SCPT tests and various geophysical methods. However, the effectiveness of these field measurements is not guaranteed and rather depends on how they are analyzed. Furthermore, a proper analysis is critical since the collected data may be used in liquefaction evaluation or earthquake ground response analyses. In these situations, it is recommended to verify the coherence between the obtained geophysical (V_s) and geotechnical (N-SPT, q_c-CPT) measurements using alternative methods (e.g., V_s-correlations, H/V method, etc...). In some situations, the correlation between the different measurements makes it easier to unambiguously define seismic wave profiles. In other cases, geophysical and geotechnical tests would provide different resolutions for V_s measurements, an issue that complicates the decision of the practitioner. In this paper, we first demonstrate the importance of the shear-wave velocity in liquefaction potential analysis. A case study performed in eastern Canada is also presented where we show the importance of the method used to calculate V_s profiles (MASW, MMASW).

1 Introduction

The disturbing effects of soil liquefaction have not sprung to the attention of researchers and geotechnical engineers until 1964 when two major earthquakes shook Anchorage, Alaska and Niigata, Japan. Both earthquakes produced spectacular examples of major damage to buildings, bridges, buried structures, highways, and utilities [1]. Liquefaction also caused severe damages in several seismic events such as in the Marina District in San Francisco during the 1989 Loma Prieta earthquake, in Kobe during the 1995 Great Hanshin earthquake, and in the Eastern part of Japan during the 2011 earthquake off the Pacific coast of Tohoku. While these cases serve as relatively recent examples, similar cases of sand liquefaction were reported much earlier [2].

2 Methodology and methods

First, the paper begins by shortly presenting the simplified methodology typically used to compute the liquefaction potential of soils in terms of the cyclic stress ratio (CSR). Second, numerical modelling is used to show some of the limitations of the simplified procedure to estimate the liquefaction potential in Eastern Canada. A particular emphasis is given on the importance to consider the regional seismicity and to define the correct soil dynamic properties to properly evaluate the liquefaction potential.

Third, a case study where SPT tests and V_s measurements were performed using different methods is also described. Although the availability of the results obtained from different tests (SPT, CPT, Vs) may be beneficial, in several cases such as the one presented in this study, those tests lead to the calculation of different liquefaction potential. Deciding how much weight should be placed on a given approach/methodology is therefore not trivial [3].

In the case study, the N-SPT values are used to evaluate both the CSR and CRR of the soil. To evaluate the CSR, the N-SPT values are first converted to shear-wave velocities (V_s) and the CRR is evaluated using the procedure presented in [4].

The liquefaction potential calculated based on the SPT tests are then compared to those obtained with the Multichannel Analysis of Surface Waves (MASW) and the Multi Modal Analysis of Surface Waves (MMASW) methods in order to compare the effectiveness of both methods. The MMASW method was developed by the Civil Engineering department of the Université de Sherbrooke in the 1990s [5]. It was developed with the aim to meet the needs for accuracy and reliability required for engineering analyses in order to overcome the higher modes difficulties meet with the use of the method SASW (Spectral Analysis of Surface Wave) developed at the University of Texas in the 1980s [6]. Compared to other surface wave methods, the MMASW method is based on the identification and separation of all surface-wave

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modes participating in the recorded traces. The latter offers several advantages such as an improved reliability and accuracy and it offers the possibility to calculate the correct Poisson ratio profiles [5, 7, 8]. With the MMASW method, surface waves are generated with a mechanical impact (a hammer of 63.5 kg dropped from a constant height of 2 m) on the ground surface and the ground acceleration is recorded using accelerometers. The energy transmitted to the ground is sufficient to characterize soil deposits to a depth of at least 50 m [5]. It is important to distinguish the patented MMASW method developed to meet engineering needs from the MASW method, developed mainly for geophysical applications [9, 24].

3 Liquefaction studies

During the last 50 years, extensive liquefaction research has been carried out by hundreds of researchers around the world and a variety of methods for evaluating the liquefaction potential of soils have been proposed. The most common of these approaches, the cyclic stress approach, is based on a comparison of the earthquake-induced cyclic shear stress ratio (i.e., the seismic demand of a soil layer, CSR) with the shear stress ratio required to cause liquefaction (i.e., the soil capacity to resist liquefaction, CRR) [e.g., 4, 10, 11]. Although it is conceptually quite simple, application of the stress approach requires careful attention to the manner in which CSR and CRR are characterized. The cyclic stress ratio, CSR can be predicted either by a detailed ground response analysis or by the simplified procedure suggested by [10] as:

$$CSR = \frac{\tau_{av}}{\sigma'_{v0}} = 0.65(\frac{a_{\max}}{g})(\frac{\sigma_v}{\sigma'_{v0}})r_d \tag{1}$$

where τ_{av} is the average peak shear stress at the depth of interest; σ_v and σ'_{v0} the corresponding total and effective vertical overburden stresses, respectively; a_{max} the peak ground surface acceleration; g the acceleration of gravity and r_d the stress reduction coefficient that accounts for the soil profile flexibility. Hence, the simplified procedure is performed without the need of detailed site response studies. However, recent studies have shown some of the limitations of the simplified procedure especially those linked to the evaluation of the stress reduction coefficient [12, 13, 14]. Our study also highlights the limitations of the simplified procedure linked to the use of a general r_d coefficient. Moreover, we show the importance of considering the local seismicity and to have access to reliable field data in order to accurately evaluate the liquefaction potential in Eastern Canada.

The early work on the characterization of the cyclic resistance ratio of soil, CRR emphasized the use of laboratory cyclic testing. Subsequent studies showed that the liquefaction resistance of soil is influenced by factors other than the initial density and stress states such as soil fabric, OCR, and the prior seismic straining [e.g., 1, 15]. Indubitably, CRR can be evaluated based on laboratory cyclic tests on undisturbed soil specimens retrieved from the potentially liquefied site. However, retrieving undisturbed samples from the field is often a difficult task limiting the usefulness of the evaluation of the liquefaction potential based on laboratory testing. Field tests therefore remain essential for routine liquefaction investigations.

3.1 Shear-wave velocity measurements

In situ geotechnical (e.g., standard penetration test blow count, N-SPT, and cone penetration resistance, qc-CPT) and geophysical methods (i.e. spectral analysis of surface waves (SASW), multichannel analysis of surface waves (MASW) and multi-modal analysis of surface waves (MMASW)) enabling the calculation of the shear-wave velocity (V_s) are now commonly used for the evaluation of CRR. Unlike N-SPT and qc-CPT that can only be measured in the field, V_s can be advantageously measured both in the field and in the laboratory under real and controlled conditions [16]. Moreover, V_s measurements are possible in hard-to-penetrate deposits. In fact, V_s appears to be preferred over N-SPT and qc-CPT in liquefaction potential analyses since it has the advantage of linking the cyclic liquefaction resistance CRR of the soil to its seismic demand CSR. Indeed, the ground seismic acceleration in Eq. 1 is associated with shear stress that is proportional to the shear strain as shown in equation 2.

$$\gamma = {}^{\tau}\!/_{G} = \frac{\tau}{G_{\max}\left(\dfrac{G}{G_{\max}}\right)} \tag{2}$$

where G and G_{max} are the soil shear modulus and initial shear modulus that is directly related to V_s. In other words, V_s is directly related to both the seismic demand CSR and the liquefaction resistance CRR as it will be discussed next.

3.2 Importance of local seismicity and site conditions

Consider a 20 m sand deposit in Montreal (Canada) region with the CSR profile estimated from cyclic shear stresses induced at different levels in the deposit by a detailed analysis of the ground response to earthquakes using the computer code, FLAC [17]. The analysis was conducted using an elasto-plastic soil model (SIG4) compatible with the G/G_{max} limits established by [10] for sand. A synthetic earthquake record with a magnitude M = 7.0 compatible with the 2005 National Building Code of Canada (NBCC) spectrum (class A) as shown in Fig. 1, is used in the analysis [18]. Note that Eastern Canadian ground motions are generally richer in high-frequency energy and of shorter durations than Western Canadian or American earthquakes of the same magnitude.

In FLAC analysis, a homogenous deposit has been considered by adopting a constant value of normalized shear wave velocity (V_{s1}) from which the shear modulus is then calculated using equation 3:

$$G = \rho V_s^2 = \rho V_{S1}^2 \left(\frac{\sigma'_v}{100}\right)^{0.5} \tag{3}$$

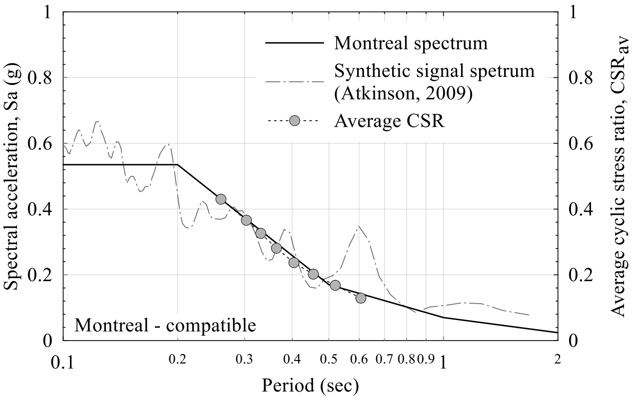

Fig. 1. Average CSR spectrums and the corresponding spectral accelerations Sa(g) for a seismic record compatible with Montreal.

where σ'_v is the effective vertical stress, ρ is the density, P_a is atmospheric pressure in the same units as σ'_v (i.e., $Pa \approx 100$ kPa if σ'_v is in kPa). The variations of the computed CSR ($0.65\tau_{max}/\sigma'_{v0}$) profiles with the adopted V_{s1} are plotted in Fig. 2.

Figure 2 shows that the cyclic stress ratio increases with the increase of shear modulus (i.e., as the soil becomes stiffer and probably denser). This implies that there is a necessity to accurately measure V_s, and the current soil classification used in Canada is not refined enough for an accurate dynamic analysis.

For example, according to the NBCC, a given soil is classified as D if the average V_{s30} value varies between 180 and 360 m/s. However, the CSR value largely varies within these velocities. In fact, the increase of CSR with the increase of V_{s1} is related to the change of the dynamic characteristic of the deposit (i.e., the increase in the fundamental frequency of the ground). The decrease in the fundamental period of the deposit (T) would in turn lead to an increase in the shear force. To illustrate this, circles corresponding to the average cyclic stress ratio shown in Figure 2 are plotted in Figure 1. Each of the 8 circles shown in Figure 1 corresponds to the mean value calculated from the CSR profiles shown in Figure 2 and can be correlated to the spectral acceleration (Sa (T)).

Likewise, Figure 3 shows the computed ranges of stress reduction coefficient r_d calculated in FLAC with the compatible synthetic record compared to the average profile suggested by [10] and the magnitude-dependent profiles proposed by [19]. Figure 3 shows that the profiles suggested by these two approaches overestimate the stress reduction coefficient calculated with FLAC. In fact, these r_d profiles were developed mainly based on Western USA deposits which are different from the Eastern Canadian deposits in terms of their seismological, geological and geotechnical characteristics.

More specifically, the application of Seed & Idriss's and Idriss & Boulanger's r_d profiles to the ongoing geotechnical applications in Eastern regions of North America would lead to over-conservatism in seismic design as shown by [20].

As demonstrated by the above hypothetical example, there is a need to validate the V_s profile implemented in dynamic analysis. The shear-wave velocity constitutes an engineering soil property that can be measured along with conventional geotechnical tests (e.g., SCPT during CPT test), with down-hole tests using the SPT hole or alternatively, by using surface wave methods (e.g., MASW; MMASW). However, these different methods may provide different resolutions for V_s measurements, and it is a difficult task to verify that the obtained V_s are correct and accurate due to the lack of reliable references for comparison.

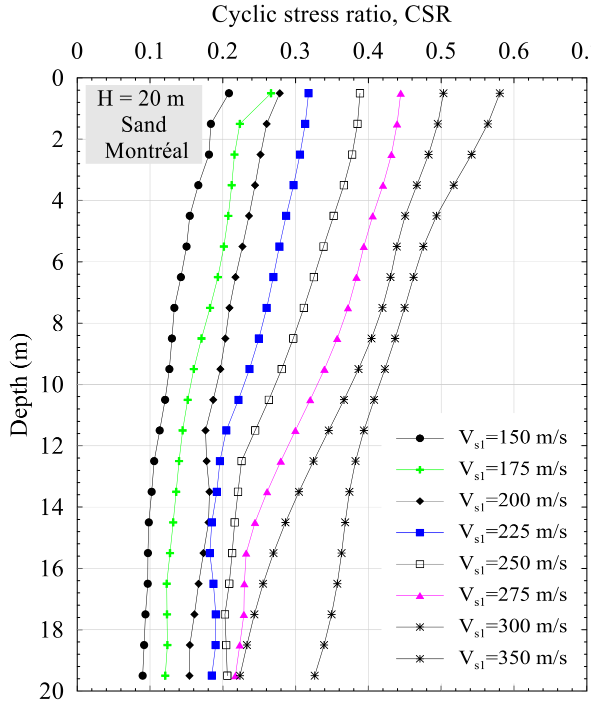

Fig. 2. Variation of the cyclic stress ratio CSR with the normalized shear wave velocity V_{s1} for the synthetic record compatible with Montreal.

4 Case study

Direct measurement of V_s on the field requires specialized equipment and technical expertise to ensure that the measured data are properly obtained and interpreted. In some cases, geophysical and geotechnical measurements may agree enabling an unambiguous decision process for the practitioners. In other cases however, geophysical and geotechnical tests would provide very different resolutions for V_s measurements, an issue that complicates the decision for the practitioners.

In this paper, a case study where it was possible to perform different types of V_s measurements is presented. The case study was performed on a soil deposit located near Québec city (Estimauville) in the province of Québec, Canada. First, SPT and MASW tests were performed to calculate the N-values and the V_s profiles respectively (Figure 4).

Although several relationships exist to convert the measured N-values to V_s, the relationship proposed by [16] is used in this study since it was shown to be accurate in Eastern Canada:

$$V_{s1} = 108.(N_1)^{0.25}.D_{50}{}^{0.18} \tag{4}$$

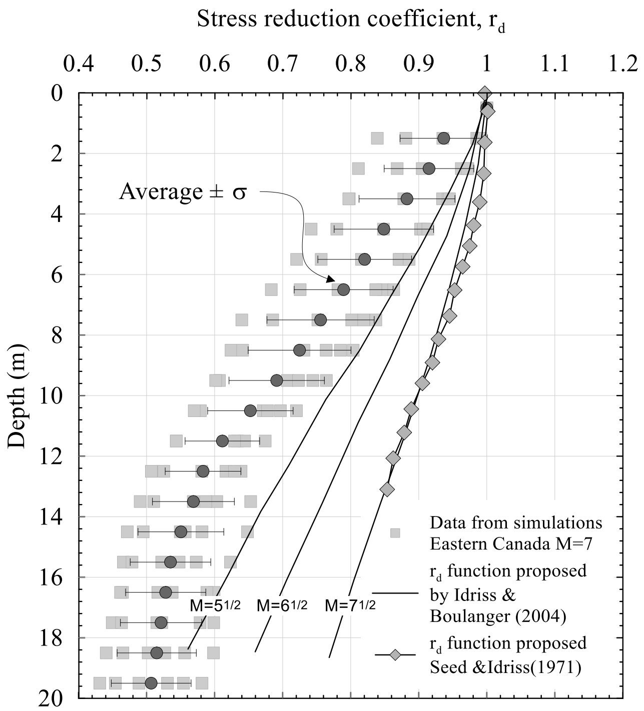

Fig. 3. Computed range of stress reduction factor compared to those proposed by [10] and [19] for a synthetic record compatible with the city of Montréal in Canada.

where V_{s1} is the stress-normalized shear-wave velocity [4], N_1 is the standard penetration blow count corrected for the effective stress and D_{50} is the mean grain size.

Within the depth where the *N*-values were obtained (0-30 m), Figure 4b shows that the V_s profiles calculated based on the *N*-values and the ones obtained with the MASW method do not agree. Indeed, the profiles obtained with the MASW method tend to have higher shear-wave velocities than those calculated base on the *N*-values. Since no *N*-values were available below 30 m, it was assumed that shortly below this depth, the V_s profile would follow the one obtained with MASW. However, given the important difference between these two Vs profiles and their impact on the calculated CSR (Fig. 2), it was questionable whether this chose was reasonable and whether the correlation used to convert the *N*-values to V_s was accurate.

Since the differences in the results obtained from both methods lead to different engineering design requirements, there was a need to conduct other tests to validate which results were accurate. Based on similar results obtained on other sites, it was necessary to perform another surface wave tests using the MMASW method.

The V_s values obtained with the MMASW method are presented in Figure 5. As shown in Figure 5, two different MMASW test lines were performed. Figure 5 shows that the V_s values determined with the MMASW method agree well with the V_s profile calculated based on the *N*-values and that below 30 m, there is no sudden increases of V_s as assumed previously. The good correlation between the V_s calculated with the MMASW method and from the *N*-values suggests that the V_s calculated with the MASW method are not accurate.

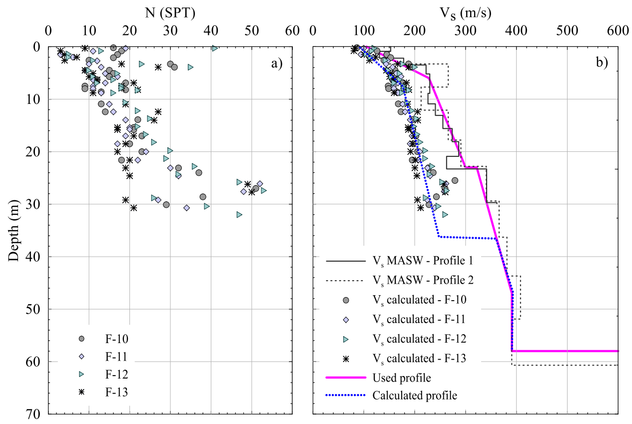

Fig. 4. (a) Measured *N*-values in four different boreholes. (b) Calculed V_s profiles based on the N-values and the MASW method. The full pink line and the dashed blue lines are the average V_s profiles calculated using respectively the MASW and the *N*-values.

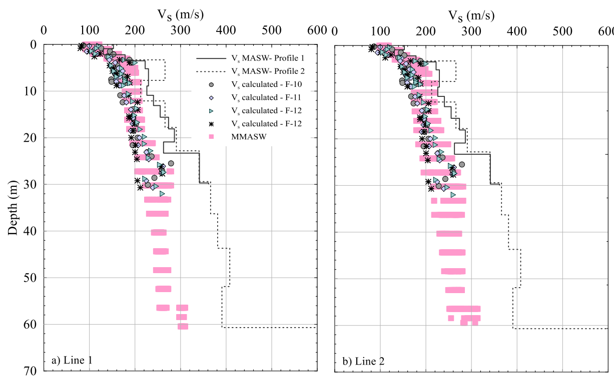

Fig. 5. Comparison between the different approaches used to calculate V_s profiles.

The latter may happen due to the presence of higher Rayleigh-wave modes in the recorded traces that are not accounted for during the inversion. Indeed, higher modes may carry a significant amount of energy, sometimes event more than the R0 mode, event in normally dispersive soil deposits [21].

The computed cyclic stress ratio, CSR, calculated based on the V_{s1} profile obtained using the MMASW and MASW methods and the *N*-SPT values (correlation) are compared to the estimated soil liquefaction resistance, CRR, calculated with the *N* data following the procedure shown by [4] in Figure 6. The CSR are calculated with the procedure presented in section 3.2. Based on the MMASW profile, the whole deposit would be safe with an adequate margin of safety. Similarly, the V_s profile calculated based on the *N*-SPT (labelled calculated profile in Figures 4 and 6) values indicates an adequate safety against liquefaction. The MASW results on the other hand indicate that the soil is susceptible to liquefaction at depths varying from 4 to 8 m. In this situation, it is difficult for an engineer to decide whether the site should be judged safe or unsafe against liquefaction.

Microtremor measurements are often used to calculate the horizontal to vertical spectral ratio (HVSR). The HVSR can be used to validate the V_s profiles calculated with other methods (MASW, MMASW, *N*-SPT) and therefore to help engineers decide which seismic-wave profile should be used for liquefaction potential analyses [22-23]. Figure 7 presents the spectral response, in terms of their transfer functions, of the same soil deposit but with their V_s profiles calculated with the MASW method (Fig.4b) and with the MMASW method (Fig.5). The periods at which there are peaks in the spectral response presented in Figure 7 should correspond to peaks in the calculated HVSR. As shown in Figure 6, the higher values of V_s found with the MASW method leads to a maximal spectral response located at lower periods (higher frequencies) than when the MMASW method was used. It can be observed that the average CSR values shown in Figure 6 correspond well to the CSR obtained from Figure 1 at the fundamental periods of 0.7 sec and 0.9 sec calculated using the MASW and MMASW profiles respectively. Considering the local seismicity of Eastern Canada, the latter is important since, as shown in Figure 1, earthquakes happening in this region tend to be rich in lower period (higher frequency) waves. The spectral response determined based on the MASW V_s profile is therefore more critical and would lead to incorrect engineering design considerations. Note that even if the MMASW V_s profile correspond well to the one calculated using *N*-SPT, it would have been interesting to validate the spectral response of this soil deposit using H/V measurements. However, no such recordings were performed on this site yet.

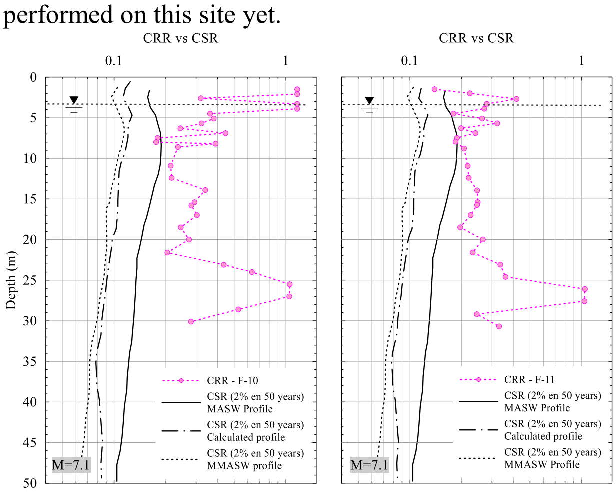

Fig. 6 Comparison between CSR calculated using 3 different V_s profiles and CRR (*N*-SPT)

5 Conclusions

For many geotechnical problems such as liquefaction potential analysis, proper knowledge of the site condition and of the local seismic activity is of outmost importance to perform reliable dynamic analysis. Indeed, the consequences of a seismic event will vary depending on the local seismic activity and the local site conditions. The traditional cyclic stress approach may therefore fail to correctly evaluate the potential of liquefaction since it does not consider the effects of the local seismicity. Also, it was shown in this study that CSR is strongly affected by the V_s profile adopted for dynamic analysis. However, identification of the site condition may also be problematic due to the diverging results obtained from different field tests (*N*-SPT, down-hole, surface-wave methods). Field data used to perform dynamic analysis should therefore be used with caution and with the knowledge that they may not always be accurate.

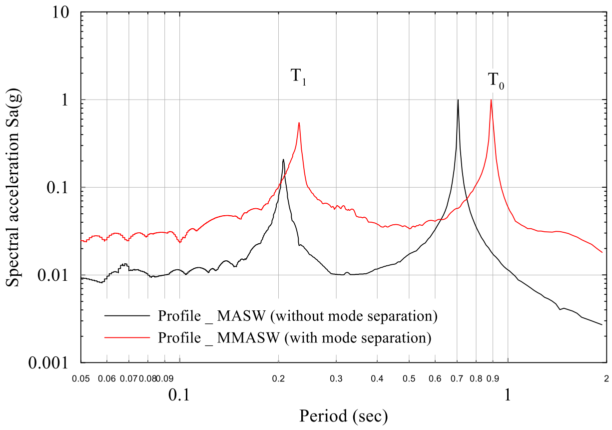

Fig. 7. Spectral responses, in terms of their transfer functions, calculated based on the V_s profiles calculated with the MASW and MMASW methods for the same soil deposit. T_0 is the fundamental period and T_1 is the first higher period.

Finally, these conclusions imply that liquefaction potential analysis must be performed by considering the local seismic activity and with the use of reliable field test data. Given the importance of V_s in liquefaction potential analysis, when possible, CPT (V_s-*qc*) and SPT (V_s-*N*) correlations as well as the H/V spectral method can be used to verify the accuracy of V_s calculated with geophysical methods.

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