Soil liquefaction evaluation using shear wave velocity

Kamil Kayabah

University of Ankara, Department of Geological Engineering, Tandogan, Ankara, 06100, Turkey

Received 5 December 1995; accepted 21 March 1996

Abstract

A reasonably good relationship between shear wave velocity (SWV) and standard penetration resistance (SPT) of granular soils in agreement with previous studies was obtained from field tests. A similar correlation between SWV and cone penetration resistance of granular soils was also obtained. Using Seed's Standard Penetration Test (SPT)-based soil liquefaction charts, new charts of soil liquefaction evaluation based on SWV data were developed for various magnitude earthquakes.

1. Introduction

The liquefaction potential of a soil layer can be determined through either laboratory tests on undisturbed soil samples or from in situ tests. A combination of these two methods can also be used in soil liquefaction analysis. Because the cost of collecting undisturbed samples is considerably high and the laboratory conditions cannot accurately simulate actual field conditions, the current tendency for evaluating the soil liquefaction susceptibility is the preference of in situ testing methods.

Standard penetration tests (SPT), cone penetration tests (CPT), flat dilatometer tests (DMT), the shear wave velocity technique (SWV) and self-boring pressure meter (SBPT) are the most commonly used in situ tests for liquefaction potential prediction. Among these testing methods, the shear wave velocity technique is thought to best represent the dynamic properties of soils. Because the soil liquefaction phenomenon is directly related to the dynamic properties of soil, the shear wave velocity technique is believed to be the best predictive method.

The shear wave velocity technique is superior to the other in situ type penetration tests because (a) the existence of large particles in the soil column (e.g., gravelly soils) likely to disable the performance of penetration tests has little effect on the SWV technique, (b) it is a non-destructive test, and (c) it is one of the few dynamic soil properties that can be measured both in the laboratory and in the field (Tokimatsu and Uchida, 1990).

The limitations of the SWV technique are: (a) the limited field performance data from earthquake areas for establishing a correlation between SWV and soil liquefaction, (b) SWV soundings are usually performed at large intervals (as large as 1 m), and (c) no soil sample is recovered through the SWV technique. Among these limitations, perhaps the limited data base is the most important limitation for the use of the SWV technique in soil liquefaction prediction. The present soil liquefaction prediction techniques using in situ tests heavily utilize the large body of SPT data collected from...
areas known to have liquefied or not liquefied under earthquake loading. The cone penetration test (CPT)-based liquefaction evaluation method also utilizes the relationship between the SPT and soil liquefaction resistance due to the good correlation between the SPT and CPT resistance of cohesionless soils.

The aim of this paper is to present soil liquefaction potential charts for various magnitude earthquakes using SWV of cohesionless soils. Seed's liquefaction charts based on SPT data were utilized to construct the baseline liquefaction evaluation charts.

2. In situ measurements of SPT, CPT, and SWV

The data used in this study were basically collected from an alluvial plain composed of silty sand. In situ tests of SPT, CPT, and SWV were performed at about 30 locations. For the SPT, both automated and hand-released hammer mechanisms were used. The theoretical energy delivered to the rods was standardized to 60%. Soil samples were collected at 1.5-m intervals. For the CPT setup, an electric cone device with a 10-cm² base area mounted on a truck was utilized. The CPT setup was capable of recording cone penetration resistance at 2-s intervals with a 1.2-m/min pushing rate. For the acquisition of the shear wave velocity data, a two-step procedure was employed. At first, the stratigraphy of the soil column was determined by using the gamma-ray logging technique. Next, the downhole shooting method was used to measure the shear wave velocity of the previously determined horizons. For the downhole test, a geophone was lowered into the borehole. Shear waves were created by hitting a sledgehammer onto a wood block which was securely placed under the wheels of a van (Fig. 1). Recorders attached to the sledgehammer and the geophone recorded the time of impact and S-wave arrival, respectively. Shear wave velocity measurements were repeated at 1-m shooting intervals. The measured shear wave velocities are presented in Fig. 2.

Most of the soil samples collected from the test locations through SPT have a fines content (material that passes through a #200 sieve) less than

15%. The mean grain size \( (D_{50}) \) for those samples varied between 0.1 and 0.25 mm (Fig. 3 and Fig. 4). The geotechnical data used in this study are only from the cohesionless materials. It was reported that some cohesive materials may liquefy under earthquake loading conditions as well (Seed and Idriss, 1982). Nevertheless, the penetration resistance of cohesive materials cannot be directly used for liquefaction prediction. Therefore, it is hard to establish the soil liquefaction potential charts for cohesive materials using the correlation between soil penetration resistance and shear wave velocity.

3. Correlation between SWV and penetration tests

The field data of SPT, CPT, and SWV collected from the alluvial silty sand deposits were evaluated to seek a correlation between the SWV and the various penetration tests. The correlation between SWV and SPT was plotted in Fig. 5. Although there is a considerable scatter in the graph, a reasonably good relationship could be observed between the standard penetration resistance and
the shear wave velocity of the examined soils. A similar relationship was also sought between the cone penetration resistance and SWV property of the same tested soils. Fig. 6 shows the correlation between SWV and CPT. The scatter in the graph is quite similar to the one between SWV and SPT.
The relationship between SPT resistance and SWV of cohesionless soils has been investigated by other researchers. Tonouchi et al. (1983) showed a good correlation between SWV and SPT-N values. They presented a relationship for this correlation in the form of \( V_s = 97 N^{0.314} \), where \( V_s \) is the shear wave velocity in m/s and \( N \) is the SPT blowcounts, based on more than 1600 data pairs. Fumal and Tinsley (1985) presented a relationship between SWV and SPT-N value in the form of \( V_s = 152 + 5.1N \) based on sand and gravelly sand soils.

The relationship between SWV and SPT-N values from the present and previous studies is plotted in Fig. 7. Curve 1 in Fig. 7 indicates the relationship between SWV and SPT-N given by Fumal and Tinsley (1985). Curve 2 is by Tonouchi et al. (1983). The curve marked number 3 indicates the relationship obtained from the present study and shown in Fig. 5. Curve 4 was obtained from Fig. 6 by using a correlation between SPT-N and CPT-\( q_e \) values obtained from tests on the alluvial deposits in this study. In order to convert the SWV–CPT-\( q_e \) relationship into a SWV–SPT-\( N_{60} \) relationship, the ratio of \( q_e/N = 5.5 \) the relationship between SWV and CPT-\( q_e \) was converted into a SWV–SPT-\( N_{60} \) relationship.

The four curves in Fig. 7 are presented in Fig. 8 in a hatched form. The average curve represented by this hatched area was found to be \( V_s = 175 + 3.75N_{60} \).

4. Liquefaction assessment using shear wave velocity

Empirical methods have been developed to evaluate liquefaction resistance of soils using penetration type in situ tests of SPT (e.g., Seed, 1979) and CPT (e.g., Seed and DeAlba, 1986). Investigations by several researchers have shown that there is a rational basis to expect a good correlation to exist between soil liquefaction resistance and soil penetration resistance (Seed et al., 1983; Tokimatsu and Yoshimi, 1983; Shibata and Teparaksa, 1988). Likewise, the SWV is also influenced by several soil parameters that influence soil liquefaction under earthquake shaking, such as relative density, overburden pressure, stress history, and geological age.

In order to establish an SWV-based liquefaction evaluation procedure, the cyclic stress ratio concept (Seed and Idriss, 1971) was utilized. The cyclic stress ratio is given as:

\[
\frac{\tau}{\sigma_o} = 0.65 \left( \frac{a_{\text{max}}}{g} \right) \left( \frac{\sigma_o}{\sigma_o} \right) r_d
\]

where \( \tau/\sigma_o \) is the cyclic stress ratio to develop liquefaction in the soil, \( a_{\text{max}} \) is the peak horizontal ground acceleration on the ground surface (in g), \( \sigma_o \) is the total stress over the layer of interest, \( \sigma_o \)
is the effective stress over the layer of interest, and \( r_d \) is the stress reduction factor.

The work of Seed and his co-workers in the form of cyclic stress versus SPT-\( N \) is presented in Figs. 9 and 10. In Fig. 9, there are three lines separating the liquefaction from the non-liquefaction zone corresponding to fines contents of 5, 15, and 35%, respectively. Fig. 10 shows the demarcation lines for liquefaction for earthquakes of different magnitude.

In order to utilize the SWV data in soil liquefaction evaluation, Fig. 11 was constructed. The two demarcation lines in the figure forming a marginal liquefaction zone correspond to the upper and lower bounds of the hatched zone in Fig. 8. Because the scatter in the SWV versus penetration test data was significant, the resulting zone of marginal liquefaction appears to be large. In order to simplify this chart into a more usable form, Fig. 12 was drawn using the average equation curve of \( V_s = 175 + 3.75N_{60} \) from Fig. 8. The users of this graph should be cautious because the demarcation line separating the liquefaction zone from the non-liquefaction in Fig. 12 is not sharp as shown in Fig. 11. Allowance should be made for a better definition of liquefaction analysis when using this chart.

Given the fact that Seed’s charts of soil liquefaction evaluation are based on overburden corrected...
penetration values, a similar procedure was employed for the preparation of SWV-based liquefaction evaluation charts. For this purpose, the overburden correction equation for shear velocity by Robertson et al. (1992) was utilized:

\[ V_{s1} = V_s (P_a / \sigma'_0)^{0.25} \]

where \( V_{s1} \) is the normalized SWV in m/s, \( P_a \) is the reference stress (typically 100 kPa or 1 bar), \( \sigma'_0 \) is the effective vertical overburden stress in the same units as \( P_a \), and \( V_s \) is the measured SWV in m/s.

In order to extend the use of SWV in soil liquefaction analysis to the magnitudes other than \( M = 7.5 \), Fig. 13 was constructed. Fig. 10 was utilized for establishing Fig. 13. To accomplish this, the information on Fig. 10 in the form of a pair of cyclic stress ratio versus the SPT-\( (N_1)_{60} \) data for a particular earthquake magnitude was transferred onto Fig. 13 as a data pair of cyclic stress ratio versus \( V_{s1} \) by utilizing the relationship between the standard penetration resistance and the shear wave velocity. Each curve in Fig. 13 represents a particular earthquake magnitude separating the zone of liquefaction from the zone of non-liquefaction.

Fig. 12. Simplified relationship between cyclic stress ratio and shear wave velocity.

Fig. 13. Soil liquefaction evaluation chart for earthquakes of different magnitude using shear wave velocity.

5. Conclusions

The test results of SWV and SPT of the present and previous studies have shown that there is a reasonably good correlation between the shear wave velocity and standard penetration resistance of granular soils. SWV also correlates with the CPT reasonably well. The charts for soil liquefaction evaluation were prepared by using the correlation of SWV data with penetration resistance data developed in this study and by combining those data with Seed's soil liquefaction evaluation charts which are based on field performance data of SPT. Future field performance data of SWV are required to validate the usability of the presented charts in engineering practice with a reasonable degree of confidence. The results of this study are based on the information that the soil layers examined have a fines content of mostly less than 15% and \( D_{50} \) between 0.1 and 0.25 mm. The soil liquefaction prediction charts developed in this study are not applicable to cohesive soils.

References