LIQUEFACTION POTENTIAL OF FINE COHESIONLESS SOILS USING THE CPT

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ABSTRACT

This paper describes an approach for interpreting cone penetration test (CPT) results to provide a direct measure for assessing soil liquefaction potential of fine granular soil deposits. The use of CPT is justified when the cost of conventional testing techniques is high or the quality of soil samples is not satisfactory. The results of a field investigation program conducted in the Mexicali Valley in the north of Mexico were used to develop correlations between, overburden pressure, \( \sigma_v' \), maximum surface acceleration, \( a_{\text{max}} \), and liquefaction potential. The method developed here suggests that CPT data can provide a measure for assessing soil liquefaction potential.

**Key words**: case history, earthquake, in–situ test, liquefaction, penetration test, sand, silt (IGC : D7/C3)

INTRODUCTION

The need to evaluate liquefaction potential of fine silty sands, sandy silts and silts has increased, as has the importance of aseismic design. One approach is to carry out undrained cyclic tests on undisturbed soil samples. However, this approach presents a problem in that, it is difficult to obtain and test high quality undisturbed samples.

It has been recognized that the liquefaction characteristics of in–situ deposits are influenced significantly by factors such as structural arrangement of soil particles, the age of the deposit and the seismic history of the deposit, all of which are altered by soil sampling.

The methods used to evaluate liquefaction potential of level ground have been studied from several different points of view. They can be divided into three groups. One is based on observations of the performance of sand deposits in previous earthquakes (field methods). The other is based on the comparison between liquefaction resistance obtained in laboratory tests (cyclic tests) and the stress and strain conditions caused by the earthquake, which are usually evaluated using simplified analytical methods. The third one is to relate the results from in–situ tests (SPT and CPT) to the results from laboratory tests on the undisturbed

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sample (Robertson and Campanella, 1985, Shibata and Teparaksa, 1988).

The results reported in this study are based on the field performance approach.

The Cone Penetration Test (CPT) is believed to offer several advantages over other in–situ methods. The CPT allows continuous registration and direct recording of the test values. In addition, there may be a great degree of accuracy and reliability.

As stated by Mitchell and Durgunoglu (1973), "the use of static cone penetrometer in soil investigation has increased markedly in recent years because the test (1) is quick, easy and economical, (2) provides information on soil characteristics in–situ, and (3) is a particularly good investigative tools for sand, where undisturbed sampling is difficult". Seemingly, Schmertman (1978), pointed out that "relative to other soil engineering methods, data for preliminary design the CPT has the outstanding advantage of often providing better speed and economy, more detailed and precise data, and data better suited to many ordinary soil engineering design problem". Moreover, the cone penetration test is becoming increasingly more popular as an in-situ test for site investigation and geotechnical design.

The objectives of this paper are: (1) to establish correlations between the end bearing $q_e$, the effective overburden pressure $\sigma'_{se}$, and the maximum surface acceleration, $a_{\text{max}}$ (for different earthquake intensities) required to cause liquefaction, (2) to present a method for liquefaction evaluation and (3) to discuss the applicability of the correlations that are proposed for the prediction of sand liquefaction potential.

FIELD INVESTIGATION

An extensive reconnaissance program (Díaz–Rodriguez, 1982, 1983) was conducted in the Mexicali Valley, located in the north of México–United States border. The Mexicali Valley has plains which contain series of deposits of silt, and clay. All of these are Quaternary marine, continental and lacustrine sediments. Plains are cut by series of geological faults, that follow a NW–SE direction, parallel to the San Andres Fault. Among these faults, Cucapá, San Jacinto, Cerro Prieto and Imperial may be considered the most important. The locations of these faults are shown in Fig. 1.

The Mexicali Valley has the highest seismicity in Mexico. The earthquakes taking place there have the following main features: superficial focus at a depth less than 300 km, strong accelerations near the epicenter, and numerous aftershocks.

On June 9, 1980 a Ms=6.7 magnitude earthquake hit the Mexicali Valley in northern Baja California, México. The epicenter was located at a distance of 11 km south east of Guadalupe Victoria town, with coordinates 32.213 N and 115.028 W. During this seismic event some ground cracking was observed and a great number of sand boils emerged, taking the form of small craters. In addition, vertical and horizontal earth displacements were observed in the zone of the farming land, which is crossed by irrigation canals.

The principal effects of this earthquake may be summarized as follows:

1) Cracking of the ground near the town of Delta, Pescadores and Mungula. The cracks observed did not indicate a definite direction. Some followed the Cerro Prieto Fault and other followed either a normal direction or a North–South direction. The longest ground crack (approximately 10 km) was located 200 m South-East of the crossing of the rail–way and the road leading to Mungula, at the Colorado River.

2) Ground displacements. The most representative ground displacements were vertical and horizontal, which were observed in some sections of the railroad tracks.

3) Sand boil formation. Sand boils in the form of craters were observed at several places. The material found in the craters consisted of very fine sands and silts. The area with the largest number of sand boils was close to Delta town. According to local information, the sand boils continued to eject water during the week following the earthquake in Chimi town.
4) Canal and drain damages. The observed damage consisted of:
   
   i) A 20 cm widening of the gap between the embankments.
   
   ii) Rotation of the concrete slope slab around its bottom edge.
   
   iii) Cracking of the bottom concrete slabs at those parts of the canals which present a change in direction, section or rigidity.

According to the damage zonation, it was decided to investigate the subsoil conditions in the Delta Neighborhood. Five sites were selected covering a zone approximately 1.5 km wide and 3 km long as shown in Fig. 2. The first step of the exploration at each site included Standard Penetration Tests (SPT) and Cone Penetration Tests (CPT) with static electrical cone (Fugro standard type) driven at a rate
of 2 cm/sec. (Díaz-Rodríguez, 1982)

In site 3' shown in Fig. 2, (Díaz-Rodríguez, 1982) there was a second step of exploration consisting of 14 borehole spread in two orthogonal axes (Fig. 3), using the SPT, the CPT, the Piezometer Probe Tests (PPT) and sampling with continuous thin wall tubes (US).

DEVELOPMENT OF A NEW CPT LIQUEFACTION ASSESSMENT METHOD

There are several reasons to expect the existence of a correlation between soil liquefaction resistance to earthquake shaking and cone penetration resistance. Both these soil properties are affected by the same fundamental factors influencing soil behavior.

In developing such correlation, the principal index used to determine soil resistance to liquefaction during an earthquake is the ratio $q_c/\sigma'_v$, where $q_c$=cone bearing and $\sigma'_v$=effective overburden pressure at depth under consideration. This parameter has the advantage of taking into account the depth of the soil layer involved and the depth of the water table.

Taking into account the above considerations, $q_c/\sigma'_v$ values were plotted in terms of the depth $z$, and were superimposed upon the corresponding stratigraphic profile. The obtained diagrams of each CPT sounding in the Mexicali Valley, which are similar to the results shown in Fig. 4, confirmed the following:

1) The intersection of the $q_c/\sigma'_v$, versus $z$ curves with the boundaries of non-liquefied fine soil strata falls approximately within a narrow band which was limited by two lines as shown in Fig. 5. These lines, whose form approximates and equation similar to that obtained by Schmertman (1978) were called left limit curves (Armijo-Palacio, 1987). The
nonliquefied fine soil strata comprise from clayey silts to high plasticity clays with friction ratio \( \left( \frac{f_s}{f_c} \right) \) values higher than 2.5\%, where \( f_s = \) shaft friction.

2) According to the observed superficial manifestations of liquefaction the soil strata that were liquefied (from low plasticity silts to very fine sands) present \( q_s/q_c' \) versus \( z \) curves that fall to the left of another narrow band which is limited by two lines as shown in Fig. 6. These limit curves, whose form also is similar to that obtained by Schmertmann (1978) were called right limit curves for a maximum superficial acceleration variable between 0.6 and 0.65\( g \) (Armijo-Palacio, 1987).

To complete this work, a comparison was made to the results obtained through the application of Seed et al. method (Seed et al., 1983, 1985) to evaluate the liquefaction potential of the explored site. From this comparison, it was concluded for this particular case, that the right limit curves and the mentioned method lead to similar results (Fig. 6).

The right and left curves as shown in Fig. 7 constitute the basis for evaluating the liquefaction potential of a fine granular soil deposit in terms of CPT. To give more general character to the method, Imperial Valley CPT data (obtained after the 15 October 1979 and 26 April 1981 earthquakes) were analyzed (Douglas and Martin, 1982; Youd and Wieczorek, 1982, 1984) in the same way as the Mexicali Valley data.
Fig. 4. Typical soil profile

Fig. 5. Limit curves for non-liquefiable fine soils strata (Mexicali Valley)

Fig. 6. Limit curves for liquefaction and no liquefaction

Fig. 7. Average left and right limit curves (Mexicali Valley)
As the data comprise sites that were liquefied for $a_{\text{max}}$ values between 0.2 and 0.8 $g$, limit curves for each of these $a_{\text{max}}$ values (Fig. 8) could be obtained, as shown in Fig. 8.

**METHOD APPLICATION**

Using this method, the liquefaction potential of normally consolidated deposits with superficial water table can be assessed. These deposits principally consist (in the upper 10 m) of fine sands to low plasticity silts, which are uncedmented and geologically young.

An assessment would consist of the following steps:

1) According to the CPT data and with the aid of soil classification charts (Seed et al., 1985) as well as with that of local correlations, the stratigraphic profile will be determined, giving special attention to the fine granular strata below the ground water level.

2) The unit weight $\gamma_t$, from which the $\sigma'$, are calculated, is estimated based upon undisturbed samples. The $q_e$ values are then nor-

3) Soils with $f_s/q_e$ higher than 2.5% are considered non-liquefiable, while those with lower values may or may not be liquefiable, depending on the position of their $q_e/\sigma'$ versus $z$ diagrams with respect to the left limit curves and the right limit curves (Figs. 7 and 8).

**APPLICATION EXAMPLE**

In order to illustrate the procedure, an example case is presented. The site corresponds to the Bennet et al. investigation (Bennet et al., 1984), on the Kornbloom road, in the Imperial valley, very near the salton Sea.

Having the CPT data (TK4 sounding) as a basis, and according to procedure indicated above, the stratigraphic profile was determined, and the $q_e/\sigma'$ versus $z$ diagram was plotted as shown in Fig. 9. The liquefaction conclusions were drawn.

**Fig. 8.** Right limit curves (Mexicali and Imperial Valley)

**Fig. 9.** Comparison of $q_e/\sigma'$ vs $z$ diagram with limit curves (application example)
1) The strata between 4.1 m and 4.7 m, and from 6.10 to the bottom (composed of clayey silt and clay) were considered non-liquefiable, as they present \( f_s/q_e \) values higher than 2.5%.

2) The remaining strata below the water table (principally composed of silt and sandy silt with a \( f_s/q_e \) lower than 2.5%) can be considered as liquefiable for 0.6g or higher \( a_{max} \) values, due to the fact that their \( q_e/a'_e \) versus \( z \) diagram falls to the right of the left limit curve and to the left of the right limit curve corresponding to the \( a_{max} \) (Fig. 9). However, strictly speaking, in Fig. 9 a thin (less than 1 m thick) strata can be seen which can be considered as liquefiable. But it rarely shows superficial liquefaction evidence due to the small soil volume they involve.

The previous analysis coincides with the field evidence because the sounding selected is located in an area in which a great number of "sand boils" developed. The crater material was composed principally of silt and sandy silt with characteristics similar to those of the material in those strata considered to be liquefiable by the evaluation procedure outline above.

**SUMMARY AND CONCLUSIONS**

The method presented in this paper permits the evaluation of the liquefaction potential in terms of the variation \( q_e/a'_e \) with the depth. One of the main advantages of this method is its simplicity. However it has to be born in mind that due to this simplicity it is only applicable in conditions similar to those under which the correlations were obtained.

The left and right limit curves (Figs. 7 and 8) and the limit values of the ratio \( f_s/q_e \) (2.5%) on which this method is based should be improved with further analyses of more data corresponding to the sites that were liquefied under the action of different earthquakes.

The penetration resistance of a soil deposit can be measured using the CPT. Therefore an evaluation of the liquefaction potential can be made by means of the proposed method. In the same way, critical areas can be identified in which a more detailed determination including additional CPT and sampling can be required.

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