EVALUATION OF THE LIQUEFACTION OF SAND BY STATIC CONE PENETRATION TEST

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ABSTRACT

The author had taken part in the site investigation of the liquefaction of sand and the static cone penetration tests in the area of Tangshan earthquake. Static cone penetration tests were performed at more than one hundred locations and the results were analysed by statistical method of discrimination function. A practical method was thus obtained for evaluating the liquefaction of sand on the site by static cone penetration tests. Good effectiveness of this method was further confirmed by the verification for its validity with the test results of Haicheng earthquake area.

INTRODUCTION

Whether or not a saturated sand foundation will be susceptible to liquefaction during an earthquake is a problem often encountered in engineering geological exploration. Until now, various methods for such evaluation have been proposed by many investigators in various parts of the world. However, almost all the practical methods are primarily based on the results of standard penetration tests. Practice has shown that the error of standard penetration test is considerable, and great dispersion of results is often found owing to the influences of such factors as the conditions of geological formation, equipments, and operation procedures of the test. All these will bring difficulties to the practical application of these evaluation methods.

In order to find a simple, rapid, accurate and cheap method of in-situ evaluation, the author proposes an approach to evaluating the sand liquefaction by basing on static cone penetration test. The occurrence of liquefaction of sand in a wide extent during the Tangshan earthquake provided favourable conditions for such study.

DESCRIPTION OF THE TESTS

In order to investigate the practical use of static cone penetration test for evaluation of the liquefaction of sand, these tests were made on more than one hundred test sites including liquefied and unliquefied places in the Tangshan seismic area. The purpose was to develop a method of evaluating sand liquefaction through the comparison of various factors involved in the two different phenomena, namely, liquefaction and no liquefaction.

The test sites were located at epicentral distances ranging from 3.1 to 105 km, but mostly within 70 km. Fig. 1 indicates the layout of the test sites, covering various areas of earthquake intensities

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7, 8, 9 and 10.

The test sites were situated in the northeast part of North Plain of China. In this region, the overburden layer of Quaternary period extends to a depth of some ten metres to several hundred metres, and there are numerous rivers. The surface layers are mostly silt and fine sand of Recent age with a low density.

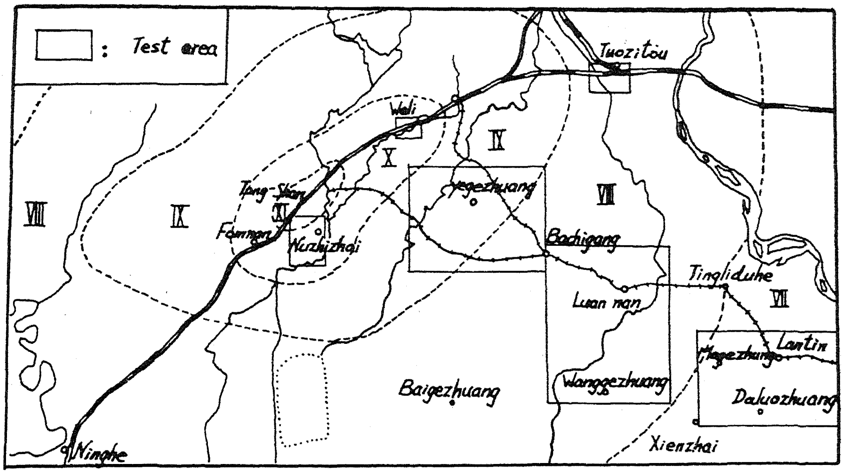

Fig. .1 Location of the test sites

The liquefied sand layers are mainly medium sand, fine sand and silt. The grain size characteristics are as follows:

Median grain size D_{50}=o.076 - 0.61 mm, mean value=0.251 mm;
Uniformity coefficient K_n=1.5 - 6.5, mean value=2.38.

Fig.2 illustrates the range of graim size distributions.

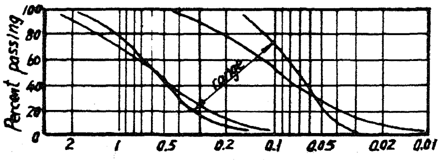

Fig. 2 Range of grain size

In the tests the hydraulic operated strain gage static cone penetrometers were used. The structure and dimension of the probe are shown in Fig. 3. The speed of penetration is 1 - 1.5 m/min.

TEST RESULTS

In the analysis of test results, the author discarded some data with low values of penetration resistance in the liquefied layers without noticeable effect on the analysis of results. All together, 125 sets of informations were collected for analysis. Among them, 94 were from liquefied sites, and 31 were from unliquefied sites. For each test a curve of penetration resistance P_s distributed along the depth can be obtained. From these curves, five parameters are selected as a basis of evaluation. They are the distance of the test site from the epicentre, D (in km); the depth of groundwater level, H_w (in m); the thickness of the overlying cohesive soil, H_o (in m); the mean depth of the middle line of sand layer investigated, H (in m); and the calculated static cone penetration resistance* of sand layer, P_s' (in kg/cm^2). Some typical results are shown in Fig. 4, from which the meaning of these parameters can be clearly seen.

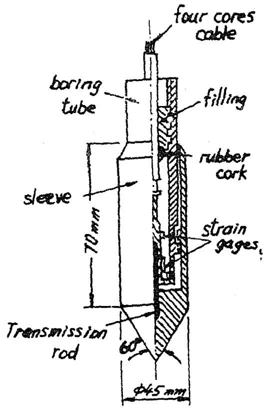

Fig. 3 Schematic diagram of probe

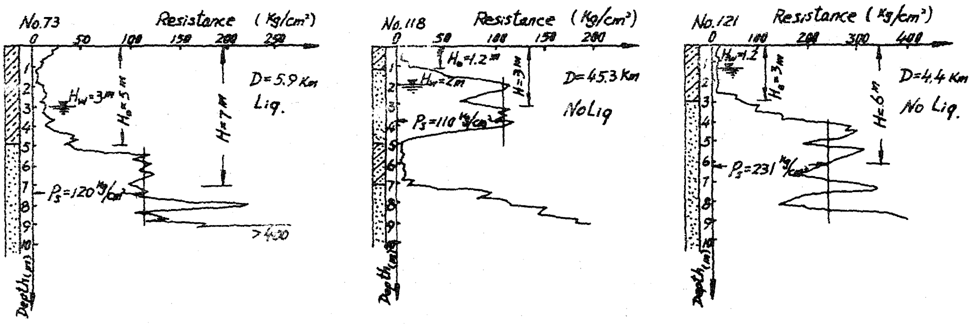

Fig. 4 Some P_s curves

The variation range of the 5 parameters for the 125 test data selected for analysis is shown in Table 1.

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* The calculated penetration resistance is referred to as the mean penetration resistance excluding the part of rising after the probe entering the sand layer and also the part of lowering before the probe entering the soft layer from the sand layer.

Table 1 Range of Test Data

Parameter			Range	Average
Distance from epicentre	D	km	3.1 - 105	39.8
Calculated penetration resistance	P'_s	kg/cm^2	34 - 423	107.1
Groundwater level	H_w	m	0.2 - 6.8	2.18
Thickness of overburden	H_o	m	0 - 10.6	2.91
Average depth of middle line of sand layer	H	m	1 - 15	4.95

ANALYSIS OF DATA

The discrimination functions are used to make statistical analysis of the aforementioned test results. Through the comparison of various kinds of discrimination functions, a method of quasi-linear discrimination function is obtained. The formula is simple and gives good result of discrimination.

$$L = \ln P'_s + 0.0215\,D + 0.0766\,H_w - 0.0017\,H + 0.0645\,H_o \qquad (1)$$

in which P'_s, D, H_w, H_o and H = discrimination factors, which are defined as before; L = discrimination function, which is also called liquefaction potential when used for evaluating the liquefaction. Basing on its value, it is possible to evaluate the possibility of the liquefaction of sand foundation.

Both the liquefied and unliquefied two events have L_i values of normal distribution. Therefore, in accordance with Gauss' distribution function the critcal value of discrimination function ($L_{cr}=5.853$) can be derived for the two events whose probabilities of success of discrimination are equal (80.9 %).

FORMULAS FOR PRACTICAL CALCULATION

For the sake of practical use, equation (1) is transformed to yield the formula for calculating the critical penetration resistance, P_{scr}:

$$\begin{aligned} P_{scr} &= \exp\,(L_{cr} - 0.0215\,D - 0.0766\,H_w - 0.0645\,H_o + 0.0017\,H) \\ &= P_{so} \times B_1 \times B_2 \times B_3 \qquad (2) \end{aligned}$$

where:

$$\begin{aligned} P_{so} &= \exp\,(L_{cr} - 0.0215\,D - 0.0766 \times 2 + 0.0017 \times 3 - 0.0645 \times 2) \\ &= \exp\,(5.576 - 0.0215\,D) \end{aligned}$$

—— Critical penetration resistance (kg/cm^2), when the average depth of the middle line of sand layer is $H = 3$ m, the depth of groundwater level $H_w = 2$ m, and the thickness of overburden layer $H_o = 2$ m;

$B_1 = \exp\left[-0.0766(H_w - 2)\right]$ —— Correction coefficient for the groundwater level;

$B_2 = \exp\left\{-0.0645(H_o - 2)\right\}$ —— Correction coefficient for the thickness of overburden layer;

$B_3 = \exp 0.0017\ (H - 3)$ —— Correction coefficient for the depth of sand layer.

The curves of correction coefficients B_1, B_2 and B_3 related to H_w, H_o and H respectively are shown in Fig. 5. From these curves, it can be seen that (1) The influence of B_3 is very small. This may be due to the fact that the static cone penetration resistance increases only a little with increasing depth and that the resistance of soil layer to liquefaction increases with the depth. Accordingly, B_3 can be approximately taken as unity; (2) when H_w and H_o vary within a certain range, the coefficients of B_1 and B_2 can be approximated by straight lines. Equation (2) then becomes

$$P_{scr} = P_{so}\left[1 - 0.065\ (H_w - 2)\right]\left[1 - 0.05\ (H_o - 2)\right] \qquad (3)$$

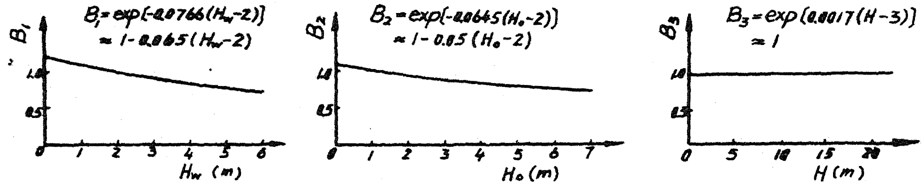

Fig. 5 Relationships between B_1 and H_w, B_2 and H_o, B_3 and H

The practical application of this equation may still present difficulty, because P_{so} depends on the epicentral distance, which is generally not easy to be determined. Moreover, the magnitude of other earthquakes will not be the same as that of Tangshan earthquake. Consequently, it is necessary to find a suitable way for easy determination of P_{so} value.

In China, the aseismic design of structures is based on the design intensity*. Some investigation data have proved that the intensity is closely related to the epicentral distance and also to the acceleration. Such question will not be dealt with in detail here. Now, a method for determining P_{so} value is given as follows: an equivalent circle with an area equal to that encircled by the isoseismal line of a particular intensity is drawn to represent that isoseismal line. Another equivalent circle representing the next isoseismal line can be similarly drawn. Then the radius of a circle which divides equally the area between the two equivalent circles will be taken as the reduced epicentral distance of the seismic

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* The intensity scale of China is divided into 12 degrees. In the design of most engineering structures, the seismic load is considered only when the intensity is at or greater than 7°. In the design code, the intensities of 7°, 8°, 9° correspond to the acceleration of 0.1g, 0.2g and 0.4g respectively.

region of a particular intensity.

$$R_{cai} = \sqrt{\frac{A_i + A_{i+1}}{2}} \qquad (4)$$

in which A_i = the area of earthquake intensity equal to or greater than intensity i, in km^2; R_{cai} = the "reduced epicentral distance" of earthquake area of intensity i, in km. The values of R_{ca} listed in Table 2 are calculated from the actual areas of different intensities of Tangshan earthquake. By substituting them into the equation for different intensities (the third row in Table) can be obtained. For some important structures, the probability of success of evaluation of sand liquefaction can be improved. The fourth row in Table 2 gives P_{so} values corresponding to a probability of success increased to 90%.

Table 2 Reduced Epicentral Distances and Critical penetration Resistances for Seismic Regions of Different Intensities

Intensity		7	8	9	10
Reduced epicentral distance	km	80.5	38.0	18.6	8.1
Critical penetration resistance	kg/cm^2	46.7	116.6	176.9	221.7
Critical penetration resistance corresponding to a probability of success of 90%	kg/cm^2	53.5	133.4	202.4	253.7
Recommended value	kg/cm^2	60-70	120-135	180-200	220-250

In addition, the P_{so} values can also be derived by another way. All the P_s' values from the raw data are corrected by the coefficients B_1, B_2 and B_3 in equation (2) to give P_{so}' values. Then, P_{so}' values are plotted against epicentral distance D as shown by the dispersed points in Fig. 6. From this figure, critical values for evaluation can be directly drawn: The two dash lines represent the critical penetration resistances calculated from the above-mentioned method. It can be seen that these two lines are essentially valid for high-intensity areas at short epicentral distances, but deviate towards lower values for low-intensity areas with epicentral distances greater than 60 km. Therefore, the solid lines are recommended to represent the critical values, i.e. the recommended values shown in Table 2.

So far, the author have obtained a comprehensive and practical method for evaluating the liquefaction of sand by static cone penetration test. In other words, the penetration resistance P_s' calculated from the in-sotu static cone penetration tests is compared will P_{scr} values derived from equation (3); if $P_s' < P_{scr}$, liquefaction will occur; and vice versa.

VERIFICATION OF VALIDITY

For verifying the validity of the proposed method, the data of

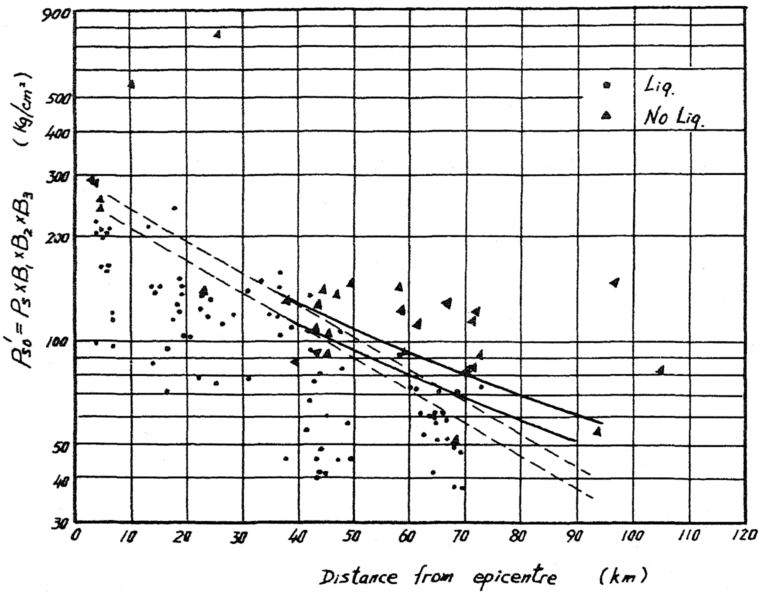

Fig. 6 Relationship between corrected value P'_{s0} and epicentral distance D

Haicheng earthquake area were studied. During the Haicheng earthquake of February 5, 1975, sand boils and water ejection were extensively found. For this earthquake area, testing data at 21 sites were checked. Among them 16 were liquefied sites. The verification showed that wrong evaluation was made only two in sites, one in liquefied site and the other in unliquefied site. The probability of success of evaluation is 91%. This shows that the method is effective.

CONCLUDING REMARKS

Through the above analysis, a simple method is developed for in-situ evaluation of sand liquefaction by static cone penetration resistance. Good validity and effectiveness of this method were verified by the data from Haicheng earthquake area.

It should be pointed out that this method is summed up for the cases of uniform medium sand, silt and fine sand foundations, and it may not be valid for the case of light sandy clay foundation with high clay content ($d < 0.005$ mm). From the experience gained in other seismic regions, it is found that the critical penetration resistance for the latter type of soil should be corrected by an appropriate value depending on the clay content, liquid limit and so on.

In addition, further researches are necessary for such problems as how to evaluate the liquefaction of foundation with alternate layers of sand and clay, how to evaluate the liquefaction of slopes, how to relate the field data to the mechanism of liquefaction, and others.

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