ON THE METHOD OF LIQUEFACTION EVALUATION
IN THE CHINESE SEISMIC BUILDING CODE

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ABSTRACT

This paper explains the bases of the criterion of sand
liquefaction evaluation used in the Chinese Seismic Build-
ing Code (TJ 11-74 & 78), and its reliability and appli-
cability are discussed. Generally, it provides satisfactory
results for sandy soils. But there were a lot of clayey
silty soils also liquefied during the 1975 Haicheng and
the 1976 Tangshan earthquakes. In such cases, criterion in
the Chinese Code always gives conservative assessments,
because the clayey silty soil is more stable than the sand
without clay particles during earthquake and the N values
of standard penetration test for the former are lower. A
suggestion is made then to modify the formula in the Code
for liquefaction evaluation based on new liquefaction
informations obtained in 1976 Tangshan earthquake and it
is also suggested to make this change in the revised code
in the near future.

INTRODUCTION

In the Chinese Seismic Building Code (TJ11-74), a method
was proposed for evaluating liquefaction potential of
saturated sand deposits besed on the experiences of several
major earthquakes which occurred in China after liberation.
The code was issued in 1974. During the 1975 Haicheng
earthquake (M=7.3) and the 1976 Tangshan earthquake (M=7.8)
sand blows developed over extensive areas and causing
severe damage to various kinds of structures. Since then,
the Chinese Seismic Building Code (TJ11-74) was revised in
the light of new information obtained in these two earth-
quakes in 1978. The method for evaluating liquefaction

potential of sand deposits in the old code (TJ11-74) is not suitable to clayey soil. This has been pointed out in the 1978 revised seismic building code(TJ11-78).

According to data obtained in the 1976 Tangshan earthquake, how to improve the method to be applied to both sandy and clayey silty soils will be discussed in this paper.

FORMULA FOR EVALUATING LIQUEFACTION POTENTIAL OF SANDY SOIL

A criterion for sand liquefaction was given in the Chinese Seismic Building Code (TJ11-74) as follows:

$$N' = \bar{N}'\left[1 + 0.125(d_s - 3) - 0.05(d_w - 2)\right] \qquad (1)$$

where N' is the critical value of standard penetration resistance for sand liquefaction when the depth of sand layer under consideration is ds, in meters, and the distance from the underground water table to the outdoor ground surface is dw, in meters; $\bar{N}'$ is the critical value of standard penetration resistance of the sand under the case of ds=3m and dw=2m. $\bar{N}'$=6, 10 and 16 coresspond to design intensity VII, VIII and IX, respectively.

According to the code (TJ11-74) saturated sand situated in ds meters deep are liable to liquefy if the actual value of standard penetration resistance is less than N' computed by Equation(1).

The N' values (6, 10 and 16) for different intensities were determined by data of several major earthquakes occurred after the People's Republic of China was founded. It may be seen in Figure 1 that the N' values can only be applied to the case of ds=3m and dw=2m. A general relationship between the critical value and the depths of sand as well as underground water table is assumed as the following function (see dotted lines in Fig. 1)

$$N' = f(d_s, d_w) \qquad (2)$$

In the case of ds=3m and dw=2m, the function can be expanded with first degree of approximation as follows. (see solid lines in Fig. 5)

$$N' = f_o + \frac{\partial f}{\partial d_s}(d_s - 3) + \frac{\partial f}{\partial d_w}(d_w - 2) \qquad (3)$$

Let ds=3m and dw=2m, and substitute them into Equation (3) we have f=f_o =N'. Then Equation (3) can be rewritten as

follows

$$N' = \bar{N}' + \frac{\partial f}{\partial d_s}(d_s - 3) + \frac{\partial f}{\partial d_w}(d_w - 2) \qquad (4)$$

when dw=2m, equation (4) becomes

$$N' = \bar{N}' + \frac{\partial f}{\partial d_s}(d_s - 3)$$

then

$$\frac{\partial f}{\partial d_s} = \frac{N' - \bar{N}'}{d_s - 3} = \frac{\Delta N'_s}{\Delta d_s} \qquad (5)$$

Similarly, when ds=3m, we obtain

$$\frac{\partial f}{\partial d_w} = \frac{N' - \bar{N}'}{d_w - 2} = \frac{\Delta N'_w}{\Delta d_w} \qquad (6)$$

As seen from Equation (5) and (6), $\frac{\partial f}{\partial d_s}$ and $\frac{\partial f}{\partial d_w}$ are the rate of change in N' value due to the change in depths of sand layer under consideration and water table for the given intensity. For simplicity, rewrite the equation (4) as follows

$$N' = \bar{N}'\left[1 + \frac{1}{\bar{N}'}\frac{\partial f}{\partial d_s}(d_s - 3) + \frac{1}{\bar{N}'}\frac{\partial f}{\partial d_w}(d_w - 2)\right] \qquad (7)$$

let

$$\frac{1}{\bar{N}'}\frac{\partial f}{\partial d_s} = \frac{1}{\bar{N}'}\frac{N' - \bar{N}'}{d_s - 3} = \alpha \qquad (8)$$

and

$$\frac{1}{\bar{N}'}\frac{\partial f}{\partial d_w} = \frac{1}{\bar{N}'}\frac{N' - \bar{N}'}{d_w - 2} = \beta \qquad (9)$$

so that equation (7) can be rewritten as follows

$$N' = \bar{N}'\left[1 + \alpha(d_s - 3) + \beta(d_w - 2)\right] \qquad (10)$$

Since N' is an unknown quantity to be determined, so the values of coefficient α and β can not be determined directly from Equation (8) and (9). However, if there are sufficient data available, the appropriate values of coefficients α and β can also be found.

For the liquefied sites, the measured N values must be less than the critical N' values, so that

$$\frac{1}{\bar{N}'}\frac{N - \bar{N}'}{d_s - 3} = \alpha^* < \frac{1}{\bar{N}'}\frac{N' - \bar{N}'}{d_s - 3} = \alpha \qquad (11)$$

and

$$\frac{1}{\bar{N}'}\frac{N - \bar{N}'}{d_w - 2} = \beta^* < \frac{1}{\bar{N}'}\frac{N' - \bar{N}'}{d_w - 2} = \beta \qquad (12)$$

For the unliquefied sites, the measured N values must be greater than the critical N' values, so that

$$\frac{1}{\bar{N}'} \frac{N-\bar{N}'}{d_s-3} = \alpha^* > \frac{1}{\bar{N}'} \frac{N'-\bar{N}'}{d_s-3} = \alpha \qquad (13)$$

and

$$\frac{1}{\bar{N}'} \frac{N-\bar{N}'}{d_w-2} = \beta^* > \frac{1}{\bar{N}'} \frac{N'-\bar{N}'}{d_w-2} = \beta \qquad (14)$$

The procedure for determining the values of coefficients α and β are the same as that for determining the N' values. Substituting the measured values of N in liuqefied and unliquefied sites into the equations on the left side of inequalities (11), (13) and (12), (14) and plotting the computed values in the α^* - I and β^* - I coordinate systems (I denotes intensity), the values α and β can be found from the borderline of the liquefied and unliquefied region. As the values of α and β have been normalized by the N' values, so that variation of the values of α and β with intensity is small. Therefore the values of α and β for different intensities are taken as 0.125 and 0.05, respectively. Thus the Equation (1) is obtained by substituting such values of α and β into the Equation (11).

Field investigations performed after the Haicheng and the Tangshan earthquakes show that the formula for evaluating liquefaction potential of sandy soil given by the Code (TJ 11-74) is in good agreement with the actual case but not suitable to the clayey silty soil.

FORMULA FOR EVALUATING LIQUEFACTION POTENTIAL OF CLAYEY SILTY SOIL

Clayey silty soil contains some clay particles which are smaller than 0.005mm. Generally, the more the clay particles in clayey silty soil, the higher the liquefied resistance, whereas the lower the value of the standard penetration resistance,N. Consequently, the liquefaction potential of clayey silty soil evaluated by equation (1) will certainly be conservative.

After the 1976 Tangshan earthquake, in areas of Tianjin where clayey silty soil liquefied and unliquefied, an analysis of grain size distribution and standard penetration test were carried out. Some results are shown in Figure 3. In the figure, the ordinate is the value of the standard penetration resistance N, and the abscissa is the inverse of the percentage of clay particle in weight,

. It should be noted that the penetration depths range from 1.0 to 12.0m, and the underground water tables range from 0.4m to 2.2m in depth.

From Figure 3, it can be seen that the data points scatter considerably, but the value of the standard penetration resistance, N, will be bigger as the inverse of the percentage of clay particles increases whether the deposits liquefied or not. It implies that there exists a certain correlation between the value of the standard penetration resistance, N, and the inverse of the percentage of clayey-sized particles, c , in addition, the penetration depth, ds, the depth of underground water table, dw, and the density of soil, D, etc., are also significant factors in liquefaction evaluation. Therefore, the relationship between value of the standard penetration resistance, N, and the factors mentioned above can be expressed as follows

$$N = F(C, d_s, d_w, D, \cdots)$$ (15)

Firstly, it is assumed that equation (15) can be separated and expressed by the product of a series of multipliers as follows

$$N = f_1(C) f_2(d_s) f_3(d_w) f_4(D) \cdots$$ (16)

Secondly, we assume that the effect of each factor to arbitrary value of C is randomly identical. Therefore, from Equation (16), the following equation can be obtained

$$N_{100} = f_1(100) f_2(d_s) f_3(d_w) f_4(D) \cdots$$ (17)

where N_{100} is the value of the standard penetration resistance corresponding to $C = 100$.

If normalizing N by N_{100} , the relationship between N and C can be obtained as follows

$$\frac{N}{N_{100}} = \frac{f_1(C) f_2(d_s) f_3(d_w) f_4(D) \cdots}{f_1(100) f_2(d_s) f_3(d_w) f_4(D) \cdots} = \frac{f_1(C)}{f_1(100)}$$ (18)

Finally, the average values of liquefied and unliquefied data can respectively be calculated for curves (1) and (2) shown in Figure 3. their equations are respectively as follows

$$(N)_{u} = (N_i)_u C^n$$ (19)

and $$(N)_{L} = (N_i)_L C^n$$ (20)

where N_1 is the value of standard penetration resistance corresponding to $C = 1$; n is the slope of the curves (1) and (2) in Figure 3; the subscripts u and L are corresponding to the cases unliquefied and liquefied, respectively.

Normalizing the equations (19) and (20) by N_{100} , then we obtain the following equations

$$\frac{(N)_u}{(N_{100})_u} = \frac{(N_1)_u}{(N_{100})_u} C^n \tag{21}$$

and

$$\frac{(N)_L}{(N_{100})_L} = \frac{(N_1)_L}{(N_{100})_L} C^n \tag{22}$$

From Figure 3 we have

$$\frac{(N_1)_u}{(N_{100})_u} = \frac{(N_1)_L}{(N_{100})_L} = \gamma_1 \tag{23}$$

and from Equation (21), (22) and (23), we obtain

$$\frac{(N)_u}{(N_{100})_u} = \frac{(N)_L}{(N_{100})_L} = \gamma = \gamma_1 C^n \tag{24}$$

From Equation (24) after normalization has been carried out it may be seen that, curve(1) coincides with curve (2) very well as shown in curve (3) in Figure 3.

Since $C=100$ and $N=N_{100}$, therefore
$$\gamma_1 \cdot 100^n = 1 \tag{25}$$
From Figure 3, we obtain $\gamma_1 = 0.1$, substituting it into Equation(25), we have
$$100^n = 10$$
or
$$n = 0.5$$

Substituting the values of γ_1 and n into Equation (24) we obtain
$$\gamma = 0.1 C^{0.5} \tag{26}$$
let
$$\frac{\overline{N}'_{corr}}{\overline{N}'} \approx \frac{N}{N_{100}} = \gamma = 0.1 C^{0.5}$$

then
$$\overline{N}'_{corr} = \overline{N}' \cdot 0.1 C^{0.5} \tag{27}$$

where $\overline{N}_{corr.}$ is the fundamental critical value of $\overline{N}'$ considering the effect of the clay particles.

Thus, by substituting $\overline{N}_{corr}'$ into Equation(1) a common equation for evaluating the liquefaction potential of sandy and clayey silty soils can be illustrated as follows

$$N' = 0.1 \overline{N}' \cdot C^{0.5} \left[1 + 0.125 (d_s - 3) - 0.05 (d_w - 2) \right] \qquad (28)$$

It should be noted that in the case of $C \geqq 100$ the Equation (28) is reduced to Equation (1).

LIQUEFACTION INDEX

The solution for evaluating the liquefaction potential is a vage idea, since the result does not point out the severity of the liquefaction consequence and no suggestion for preventive measures to be taken is made. The liquefaction consequence depends on the extent and position of the liquefied soil. Therefore we have to find an index to reflect the synthetical effects of these factors. This index is called liquefaction index.

According to the experiences obtained from the Haicheng and Tangshan earthquakes soil liquefaction may take place as deep as 20m below the ground surface. Thus the liquefaction index can be defined as follows

$$I_L = \int_0^{20} (1 - \frac{N'}{N}) W(z) dz \qquad (29)$$

where I_L is the liquefaction index; $W(z) = 1.0 - 0.05 Z$ is the weighted factor for liquefaction depth; and Z is the depth of liquefied soil layer below ground surface.

In the calculation of liquefaction index, the layers of unliquefied soil is not taken into account, just because they are not liquefied. For example, they may be soil layers which located above underground water table, sand layers beneath underground water table with standard pentration resistance $N < N'$, cohesive soil with the percentage of clay particles greater than 10%, and sand-gravel layers etc..

In conventional practice, the following formula can be applied for calculating the liquefaction index.

$$I_L = \sum_{i=1}^{n} a_i W(z_i) \qquad (30)$$

where a_i is the influence coefficient of liquefaction range at depth z_i as shown in Figure 4 (b). It is apparent that the greater the value of liquefaction index, the

severer the damage to structures. Therefore, a measure
for liquefaction prevention can be adopted according to
liquefaction index as shown in the following table for
example.

liquefaction index	structure	
	common	special
I_L 0.5	shallow foundation	massive founda.
0.5 I_L 1.5	massive foundation	deep foundation
I_L 1.5	deep foundation	

CONCLUSIONS

On the basis of what mentioned above, it seems the main
facotrs which affect soil liquefaction during earthquake
have been taken into account in the Equation (28) in a
simple way, and the liquefaction potential for both sandy
and clayey silty soils can be evaluated with considerable
accuracy. The culculating procedure is very simple, and
the data required for evaluating the liquefaction poten-
tial are easy to obtain. Prediction of soil liquefaction
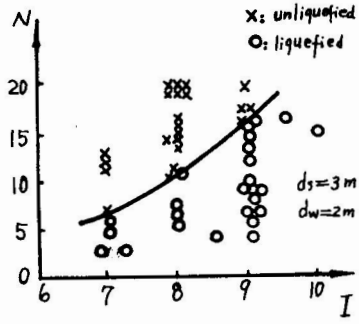can be achieved successfully using Equations (28) and (30).
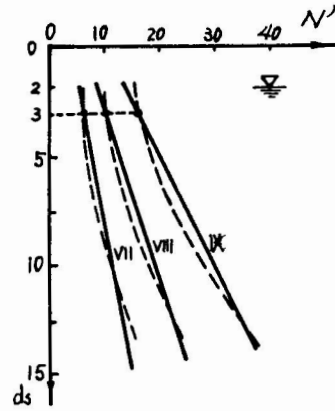
Fig. 1 Change of N' with I
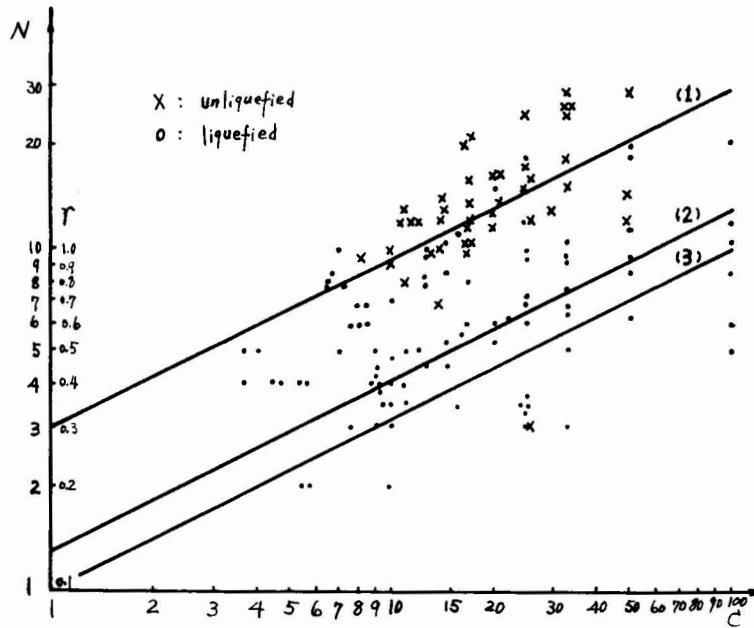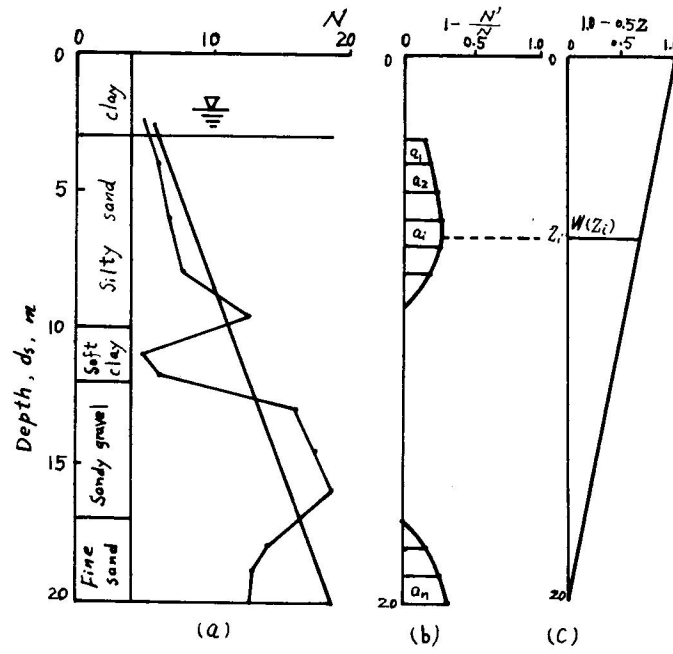

Fig. 2 Change of N' with ds

Fig. 3 Relationship between N and C

Fig. 4 Calculation of liquefaction index