METHODS FOR THE PREDICTION OF SAND LIQUEFACTION

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SUMMARY

Some thresholds of sand liquefaction are given in the paper based on the earthquake experience in China. The bases of the method for the prediction of sand liquefaction given in the Chinese aseismic building code are discussed. A method for computing the factor of safety and the degree of liquefaction of soil element is presented, based on the analysis of dynamic response of flat ground or slope to the earthquake motions.

INTRODUCTION

There are many factors that influence sand liquefaction, therefore, it is a complicated problem to predict the sand liquefaction. For the practical purpose, it is necessary to have a deep understanding of liquefaction by all means step by step. Because of this, we have to take the following three steps to predict the sand liquefaction occurred at the given sites. Firstly, estimate preliminarily the liquefaction potential at the given site during earthquake, based on some empirical data; Secondly, field test is made also for further investigation of the liquefaction potentials at the given site; finally, analyse the dynamic response of sand layer lying under important structures to the earthquake motions and investigate the liquefaction potential of the site, based on the gained results. These problems will be discussed later in the following sections.

THRESHOLDS OF SAND LIQUEFACTION

It is possible to evaluate preliminarily the sand liquefaction potential of the given site from the thrsholds of the affecting factors of sand liquefaction, based on earthquake experience. There are many factors which have effect on the sand liquefaction. These factors are grouped into three categories: (1) The strength of earthquake, i.e., magnitude, epicentral distance or intensity; (2) environment conditions, i.e., depth of sand element and water table below the ground surface, which show the stress condition prior to earthquake in the sand layer; and (3) characteristics of soil, i.e., type of soil and its physical properties. Some information related to the thresholds of sand liquefaction is given based on the earthquake experience in China as follows.

The information of sand boils in China before 1955, about nine hundred years ago, are shown in Fig. 1. An empirical relationship between the maximum epicentral distance of the liquefaction site and magnitude (1) is founded as follows

$$D_{max} = 0.812 \times 10^{0.87(M-5)} \qquad (1)$$

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density of the point A, situated outside the cube, are rather low, the sand is not liable to liquefy, because the clay content in it is large. Contrarily, although the effective burden pressure and relative density of point B situated inside of the cube are both considerable high, the sand is liable to liquefy because the grain size composition of the sand is suitable for liquefaction.

METHOD FOR THE PREDICTION OF SAND LIQUEFACTION IN THE CHINESE ASEISMIC BUILDING CODE (2)

A criterion for sand liquefaction was given in the Chinese "Aseismic Design Code for Industrial and Public Buildings" (TJ11-74) as follows:

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

in which N' = critical numbers of blows in standard penetration for sand liquefaction when the depth of the saturated sand is d_s, in meters, and the distance from the underground water table to the outdoor ground surface is d_w, in meters; $\bar{N}'$ = the critical numbers of blows in standard penetration of the sand when d_s =3 m and d_w =2 m. $\bar{N}'$ =6, 10 and 16 when the design intensity is VII, VIII and IX, respectively.

According to the code, saturated sands situated in d_s meters deep are liable to liquefy if the actual numbers of blows in standard penetration is less than N', computed by equation (2).

The $\bar{N}'$ values (6, 10 and 16) for different intensities are determined by the data of several major earthquakes occurred after the People's Republic of China was founded. It may be seen that, the $\bar{N}'$ values shown in Fig. 3 can only be applied to these cases when d_s =3 m and d_w =2 m. In order to set up the general relationship between the critical value and depth of sand as well as water table, assume there exists the following function (3) (see dotted lines in Fig. 4).

$$N' = f(d_s, d_w) \qquad (3)$$

In case d_s =3 m and d_w =2 m, the function is expanded and the following equation is obtained (see solid lines in Fig. 4).

$$N' = f_0 + \frac{\partial f}{\partial d_s}(d_s-3) + \frac{\partial f}{\partial d_w}(d_w-2) \qquad (4)$$

when d_s =3 m and d_w =2 m, then $f = f_0 = \bar{N}'$, so equation (4) can be written as follows

$$N' = \bar{N}' + \frac{\partial f}{\partial d_s}(d_s-3) + \frac{\partial f}{\partial d_w}(d_w-2) \qquad (5)$$

when d_w=2 m, equation (4) becomes

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

so that the following relationship can be obtained

$$\frac{\partial f}{\partial d_s} = \frac{N'-\bar{N}'}{d_s-3} = \frac{\Delta N_s'}{\Delta d_s} \qquad (6)$$

Similarly, when d_s =3 m,

$$\frac{\partial f}{\partial d_w} = \frac{N'-\bar{N}'}{d_w-2} = \frac{\Delta N_w'}{\Delta d_w} \qquad (7)$$

As seen from equations (6) and (7), $\frac{\partial f}{\partial d_s}$ or $\frac{\partial f}{\partial d_w}$ is the rate of change of N' value due to the change of depth of sand or water table for the given intensity. For simplicity, rewrite the equation (5) as follows

$$N' = \bar{N}'\left[1 + \frac{1}{\bar{N}'}\frac{\partial f}{\partial d_s}(d_s - 3) + \frac{1}{\bar{N}'}\frac{\partial f}{\partial d_w}(d_w - 2)\right] \tag{8}$$

taking

$$\frac{1}{\bar{N}'}\frac{\partial f}{\partial d_s} = \frac{1}{\bar{N}'}\frac{N' - \bar{N}'}{d_s - 3} = \alpha \tag{9}$$

$$\frac{1}{\bar{N}'}\frac{\partial f}{\partial d_w} = \frac{1}{\bar{N}'}\frac{N' - \bar{N}'}{d_w - 2} = \beta \tag{10}$$

so that equation (8) can be written as follows

$$N' = \bar{N}'\left[1 + \alpha(d_s - 3) + \beta(d_w - 2)\right] \tag{11}$$

As N' is an unknown quantity to be determined, so the values of coefficient α and β cannot be determined directly from equations (9) and (10). However, if there are sufficient available data, the appropriate values of coefficient α or β can also be found.

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

$$\frac{1}{\bar{N}'}\frac{N - \bar{N}'}{d_s - 3} = \alpha^* < \frac{1}{\bar{N}'}\frac{N - \bar{N}'}{d_s - 3} = \alpha \tag{12}$$

$$\frac{1}{\bar{N}'}\frac{N - \bar{N}'}{d_w - 2} = \beta^* < \frac{1}{\bar{N}'}\frac{N - \bar{N}'}{d_w - 2} = \beta \tag{13}$$

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

$$\frac{1}{\bar{N}'}\frac{N - \bar{N}'}{d_s - 3} = \alpha^* > \frac{1}{\bar{N}'}\frac{N - \bar{N}'}{d_s - 3} = \alpha \tag{14}$$

$$\frac{1}{\bar{N}'}\frac{N - \bar{N}'}{d_w - 2} = \beta^* > \frac{1}{\bar{N}'}\frac{N - \bar{N}'}{d_w - 2} = \beta \tag{15}$$

The method for determining the values of coefficients α and β is the same as that for determining the N' values. Substituting the measured values of N in liquefied or unliquefied sites into the equations on the left side of inequalities (12), (14) and (13), (15) and plot the computed values in the α^*-I or β^*-I coordinate systems (I denotes intensity), thus the values of α or β can be found from the boundary line of the liquefied and unliquefied region. As the values of α and β have been normalized by the $\bar{N}'$ values, so that, variation of the values of α or β with intensity is small, therefore the average values of α and β for different intensities are taken as 0.125 and -0.05 respectively, so that, equation (2) is obtained by substituting such values of α and β into equation (11). Because of lack of the field data, the simplified procedure for evaluating soil liquefaction potential (4) presented by Seed et al. is used in the determination of α and β .

Field investigations show that the method for the prediction of sand liquefaction given by the Chinese Aseismic Code is in good agreement with the actual case in China.

FACTOR OF SAFETY AND DEGREE OF LIQUEFACTION OF SOIL ELEMENT

For foundation of important structures, such as dams etc., earthquake response sometimes must be made and used to determine the liquefaction potential of saturated sand layers under the structure. The method for this purpose (5) is described briefly as follows:

1. Compute the static stresses and the seismic stresses in the sand layer.

2. Compute the factor of safety of soil elements by the following equation

$$F_d = \frac{tg\,\varphi}{tg\,\bar{\varphi}} \tag{16}$$

For cohesive soils,

$$tg\,\bar{\varphi} = \frac{\frac{1}{2}(\sigma_{1e} - \sigma_{3e})\,Cos\,\varphi}{C \cdot ctg\,\varphi + \frac{1}{2}(\sigma_{1e} + \sigma_{3e}) - \frac{1}{2}(\sigma_{1e} - \sigma_{3e})\,Sin\,\varphi} \tag{17}$$

For cohesionless soils,

$$tg\,\bar{\varphi} = \frac{(\sigma_{1e} - \sigma_{3e})\,Cos\,\varphi}{(\sigma_{1e} + \sigma_{3e}) - (\sigma_{1e} - \sigma_{3e})\,Sin\,\varphi} \tag{18}$$

in which F_d = factor of safety of soil elements; φ = dynamic friction angle of soil, $\bar{\varphi}$ = the shear resistance angle of soil element on the failure plane under given stress condition, σ_{1e} = the maximum normal stress of the soil element during earthquake (including static stress); σ_{3e} = the minimum normal stress of the soil element during earthquake (including static stress).

Stability of the soil elements may be evaluated based on the computed values of factor of safety by the following condition.

$F_d > 1$, stable or not liquefied.
$F_d = 1$, limit of stable or initially liquefied.
$F_d < 1$, unstable or completely liquefied.

3. Determine degree of liquefaction of the soil elements by the following equations.

$$G_L = \frac{N}{N_i} \tag{19}$$

$$N_i = 10^{\frac{1}{m_i}\left[\left(\frac{\sigma_{od}}{\sigma_{3c}}\right)_{10} - \left(\frac{\sigma_{od}}{\sigma_{3c}}\right)_i\right] + 1} \tag{20}$$

in which G_L = degree of liquefaction of the soil elements; N = equivalent number of cycles of soil element during earthquake; N_i = number of cycles required to induce initial liquefaction in the given soil element, m_i = property constant of soil; $\left(\frac{\sigma_{od}}{\sigma_{3c}}\right)_{10}$ = stress ratio in the triaxial test for the 10th cycles; $\left(\frac{\sigma_{od}}{\sigma_{3c}}\right)_i$ = stress ratio required to induce initial liquefaction.

The liquefaction potential of the soil element may be evaluated based on the computed degree of liquefaction by the following conditions.

in which D_{max} = maximum epicentral distance of the liquefaction site in kilometers; and M = magnitude of earthquake.

The maximum epicentral distance of the liquefaction site in the 1975 Haicheng earthquake (M=7.3) and the 1976 Tangshan earthquake (M=7.8) is 100 km and 170 km, respectively, as shown in Fig. 1 by the mark ▲ , both are close to the values computed by equation (1).

As seen from equation (1), when magnitude M=5, sand boils can only occur in the epicentral area. The intensity in the epicentral area corresponding to magnitude M=5, is VI, it means that the minimum intensity in which liquefaction will occur is VI.

A large number of joints of concrete casings in irrigation wells in liquefied areas during the 1976 Tangshan earthquake were sheared laterally in the depth 5 m to 20 m below the ground surface and at the same times, the well was blocked by the sands. It is suggested that the maximum depth of sand liquefaction during earthquake can reach as far as 20 m under the ground surface.

The depth of the water table in the heavily liquefied area was generally not more than 3 m, and it is hard to find the sand boils at the site if the depth of water table exceeds 5 m. It seems that the maximum depth of water table for sand liquefaction is about 5 m. Sand soils spouted to the surface during the Haicheng and the Tangshan earthquake were composed of silty clay, silty sand, fine sand, medium sand and coarse sand. Generally, the physical properties of these soils are as follows:

Mean size diameter d_{50} = 0.015-1.0 mm.
Uniformity coefficient $U_c < 10$.
Relative density $D_r < 75\%$.
Clay content ($d < 0.005$ mm) $< 10\%$.
Plastic index $I_p < 10\%$.

Simplified thresholds for sand liquefaction based on the data of the 1975 Haicheng earthquake have been given as follows:

	VII	VIII	IX
mean size diameter d_{50}(mm)	0.02-0.10	0.02-0.20	0.015-0.50
relative density D_r (%)	< 55	< 70	< 75
effective overburden pressure σ_0' (kg/cm^2)	< 1.0	< 1.5	< 2.0

The above described threshold values for each intensity define a cube in a geometry sense. The higher the intensity, the greater the volume of the cube (Fig. 2). In practice, it is assumed that of a point, determined by the actual property indices of the site falls in the cube, liquefaction will occur at the given site.

Such geometric representation of threshold values not only gives us an intuitive feeling about the liquefaction potential of sands, but also shows the combined effect of the influencing factors. For example, for intensity VII, although the effective overburden pressure and the relative

$G_L > 1$, completely liquefied.
$G_L = 1$, initially liquefied.
$G_L < 1$, not liquefied.

During the Tangshan earthquake, the earth dam across the Dou River was seriously damaged (Fig. 5). The main dam was 22 m high, and 1,700 m long. The soil condition of the site is shown in Fig. 5. Analysis of static stress (Fig. 6) and dynamic response (Fig. 7) of the dam to earthquake motion are made in order to investigate the cause of failure in the dam. The computing results demonstrate that, the sand layer in the dam foundation liquefied during the Tangshan earthquake (Fig. 8).

CONCLUSION

Occurrence of liquefaction of saturated sand induced by earthquake depends on a lot of factors. Summarizing the earthquake experience, in order to find out thresholds of sand liquefaction, may give aid to predicte sand liquefaction. But the data are not adequate for this purpose. It is necessary to accumulate them gradually.

The method for the prediction of sand liquefaction given in the Chinese Aseismic Code reflects the effect of some factors on sand liquefaction. This method is simple in use and convenient to put into practice. Experience of the Haicheng and the Tangshan earthquakes demonstrate that, in general, this method can give us a satisfactory results.

The proposed methods for determining the factor of safety and degree of liquefaction of soil elements, based on the results of analysis of the dynamic response of the sand layer to the earthquake motion, can be used in both level surface and slope.

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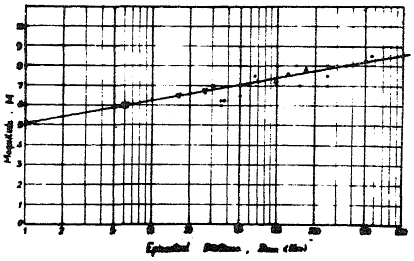

Fig. 1 Max. distance from the liquefied site to Epicenter

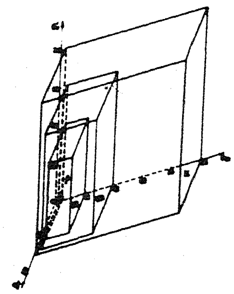

Fig. 2 Geometrical representation of soil liquefaction thresholds

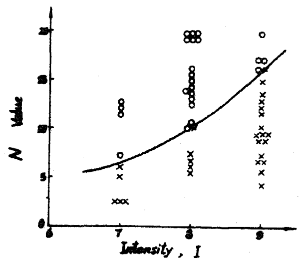

Fig. 3 Relation between values and intensity

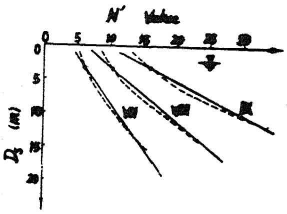

Fig. 4 Variation of values with the depth of liquefied sand

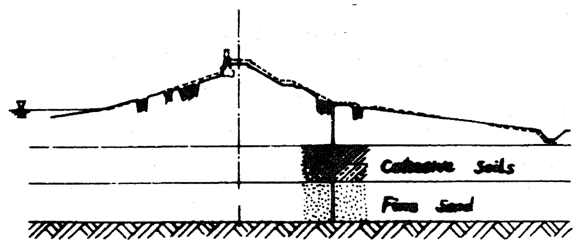

Fig. 5 Cross section of earth dam of Douhe Reservoir

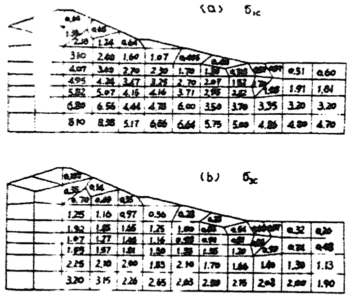

Fig. 6 Distribution of static stress in the studied section

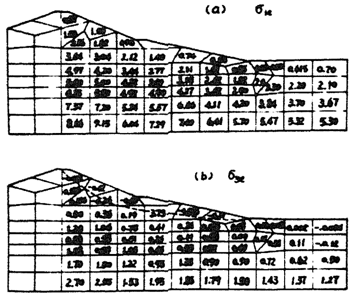

Fig. 7 Distribution of earthquake stress including the static stress

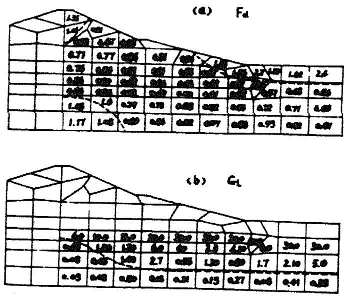

Fig. 8 Factor of safety and degree of liquefaction