ISGSR 2011 - Vogt, Schuppener, Straub & Bräu (eds) - © 2011 Bundesanstalt für Wasserbau ISBN 978-3-939230-01-4

The evaluation of liquefaction potential of oil-containing sand under cyclic loading

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ABSTRACT: Taiwan is a country lacking crude oil. All crude oil is imported from other countries and is transported to storage tanks. In the process of transporting, spills occur leading to crude oil infiltrating into the soil. The engineering properties of soil may change due to the presence of crude oil. Moreover, the earthquakes are frequent in Taiwan, and the potential risks leading to soil liquefaction are relatively high. The dynamic strength and bearing capacity of oil containing soil will decrease under cyclic loading even when the static loading is unchanged. Hence, earthquake loading of oil storage tank areas pose a potential risk for weakened soils due to the oil in the soil.

In this study, oil containing sand was subjected to loading in a cyclic triaxial test system. The sand was poorly graded and fine grained, typical of that found in southern Taiwan. Tests were conducted on the pure sand, sand with an oil content of 10% by void space, and sand with three contents by weight (1.0%, 1.5% and 2.0%) of carboxymethyl cellulose (CMC) to improve the strength of the oil sand. Three relative density (D_r) were selected: 30%, 45% and 60% and confining stresses of 50, 100 and 150 kPa were used. Through consideration of these variables, the dynamic behavior of oil containing soil was studied and the potential of soil liquefaction and liquefaction resistance were analyzed.

The results indicate that the oil reduces the cyclic strength of the sand by more than 50%. Using the CMC material increases the cyclic soil strength back to that of the oil-free sand. The effect of relative density and confining stress conditions were also studied. The overall results showed that the cyclic strength and liquefaction resistance of oil containing sands can be restored with the addition of small amounts of CMC and is an efficient method to improve ground that contains oil.

Keywords: Oil sands; Cyclic triaxial system; Soil liquefaction; Relative density

1 INTRODUCTION

Taiwan is a county lacking crude oil and all crude oil is imported and placed in storage tanks. The process of filling and emptying the storage tanks presents an opportunity for leakage of the oil from the pipes connected to the storage tanks. This oil finds its way into the underlying soils. In southern Taiwan, the soil beneath the oil tanks is typically a sandy soil. Moreover, the strength of soil will decrease due to the crude oil infiltrates into the soil. Taiwan is located in the Pacific earthquake zone and subject to numerous earthquakes each year.

A study by Yang (2000) showed that adding oil up to 10% by volume increased the static strength of the sand through the addition of a pseudo-cohesion. However, in terms of dynamic strength, when the oil content increases, the cyclic stress ratio (CSR) decreases. The reduction of CSR means the reduction of the liquefaction resistance. The results are different between the static triaxial test and the cyclic triaxial test because the pseudo-cohesion is broken under the cyclic loading and the lower the permeability of oil-containing sand. Due to the reduction of the permeability of soil, the excess pore water pressure will increase rapidly once the dynamic loads are applied. The mechanism of the soil liquefaction is the excess pore water pressure induced by earthquake load cannot dissipate immediately leading to reduction in the effective stress of soil. The soil suddenly loses the shear strength and bearing capacity.

The influential factors of soil liquefaction are summarized as (1) relative density (Seed, 1968; Mulilis, 1975; Wu, 1979), (2) effective stress (Kishida, 1969), (3) grain size distribution, (4) fines content. Hsiao *et.al* (1983) found that adding a stabilizer to a soil with high liquefaction potentialcan increase the resistance under cyclic loading.

In this study a chemical stabilizer in varying amounts is added to the soil and the CRS determined. The results show that the addition of a small of amount of stabilizer, between 1 and 2% by weight, returns the cyclic shear strength back to that of uncontaminated soil.

2 TEST PROCEDURE

In the experimental procedures, several conditions were controlled to model the in-situ conditions. The influencing factors of dynamic strength of oil-sand are mainly (1) confining pressure, (2) relative density, (3) oil content and (4) stabilizer content. According to previous research, when the confining stresses are greater than 200 kPa in the sand, the liquefaction potential of the soil is very low. Accordingly, in the tests, 50, 100 and 150 kPa are selected as the confining pressures. Generally, liquefaction does not occur when the relative density, D_r is greater than 70%. The stabilizer was added in increments of 1, 1.5 and 2% by weight. The crude oil content used was 10% based on the volume of voids in the soil. The sand used for the testing was a local sand called Li-Kang sand. The experimental flow chart is shown in Figure 1. This study adopted the CKC cyclic triaxial test system to test the soil mixed with 10% of oil by volume.

2.1 Soil Sample Preparations

The Li-Kang sand was used and remolded at relative densities 30%, 45% and 60%. The physical indices of Li-Kang sand are specific gravity, G_s=2.71, average particle size, D_{50}=0.42, uniformity coefficient, C_u=2.2, coefficient of gradation, C_c=1.2 and the soil is classified as SP according to Unified Soil Classification System (ASTM 2487-00).

2.2 Soil Stabilizer

The stabilizer used was sodium carboxymethyl cellulose (CMC), which is a white or a slightly yellowish, almost odourless and tasteless hygroscopic powder consisting of very fine particles, fine granules. CMC is a non-toxic white powder, can be absorbed by the water. The solution is cohesive and will form a membrane. The chemical equation is as follows

$$\mathbf{Cell\text{-}(OH)_3+ClCH_2COONa+NaOH \rightarrow Cell\text{-}(OH)_2OCH_2COONa+NaCl+H_2O} \quad (1)$$

CMC stabilizer is often used in ground improvement, a major component of stabilizing solution which added to the sand layer to increase the stability of the trench. Particularly in salty sand, the salt-resisted CMC is used to improve the ground.

2.3 Definition of Failure

In general, when cyclic triaxial tests are performed, two types of liquefaction failures can be defined in the saturated sand. One definition is based on the effective stress concept, in which soil liquefaction has been defined as occurring when the pore water pressure equals the confining pressure in the chamber during cyclic load. The other definition is based on strain control.

Seed and Lee (1966) performed triaixial tests using Sacramento sand with different relative densities and defined the corresponding axial strain at a certain value as failure. However, Poulos (1985) thought the failure in terms of axial strain was not persuasive, the axial strain can only determine deformation, not failure. Accordingly, the effective stress reducing to zero is adopted as the definition of soil liquefaction in this study.

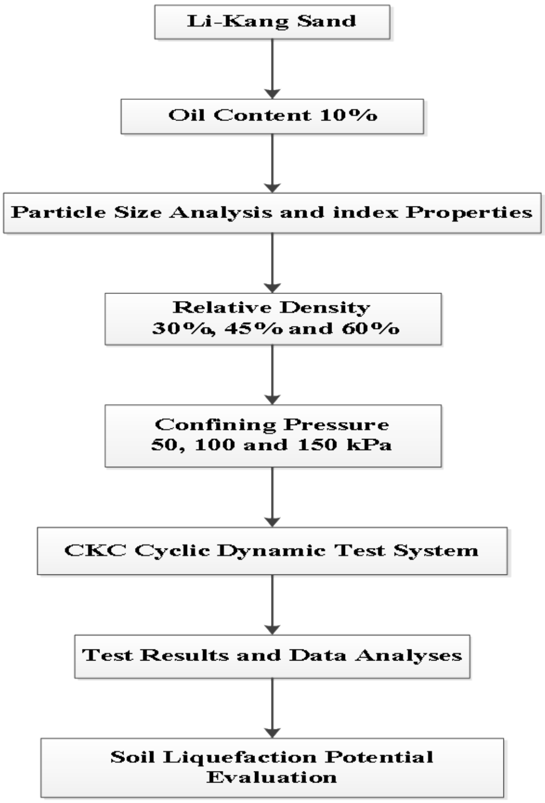

Figure 1. The scheme of testing soil containing crude oil and stabilized with CMC using cyclic triaxial testing system

3 TEST RESULTS AND INTERPRETATION

Three different relative densities were used to remold the samples and three confining pressures were used to test the soils. Six sets of data are given after each test: Number of cycles, cyclic deviator stress, axial strain, confining pressure, effective stress and volume change. Four figures can be formed to illustrate the change of the cyclic strength. According to Yang's (2000) study, the dynamic strength is lowered due to the presence of the soil. The results of the cyclic tests for various combinations of relative densities, confining pressures, and stabilizers are shown in Figure 2 through Figure 4.

4 DISCUSSION

According to Seed et. al (1975), a method was proposed to use the results from cyclic triaxial test to evaluate liquefaction resistance. Based on the earthquake scale M=7.5, the CSR corresponds to number of cycle, N equal to 15 can be used. However, the correction factors of remolded sample are based on wet side compaction, OCR, coefficients of lateral earth pressure and so on. The CSR obtained from the cyclic triaxial test multiply by 0.7 is the CSR leads to soil liquefaction. According to the definition of factor of safety against soil liquefaction, it can be mathematically expressed as the following form

$$FS = \frac{CSR_{(corrected)}}{\left(\tau_{avg} / \sigma'_v \right)} \qquad (2)$$

Seed (1975) suggest factor of safety against soil liquefaction should range between 1.25 and 1.5. The τ_{avg}/σ'_v is based on 0.65 τ_{max}/σ'_v and M equal to 7.5. The number of cycles from cyclic triaxial test is 15. However, if the Richter scale, M is other than 7.5, the cyclic stress ratio (CSR) induced by the earthquake has to be modified. The corresponding number of cycles is also different. The relationships between earthquake magnitude and modification factors are listed in Table 1.

In order to evaluate the liquefaction potential, the scheme shown in Figure 5 is presented to be followed according to different site conditions, earthquake magnitude and the combination of equivalent number of cyclic cycles and modification factor.
Three different relative densities were tested, 30, 45, and 60%. Due to space limitations, only the 45% results are reported herein. Similar trends occurred with the other two relative densities. The results of CSR with respect to the number of cycles are shown in Figure 2, Figure 3 and Figure 4 based on the soil with relative density 45% under different confining pressures.

The results presented in Figure 2 to Figure 4 are the cyclic strength ratios of oil-contaminated soil, pure sand and the stabilized soil with the relative density, D_r=45% under the confining pressures, 50, 100 and 150 kPa, respectively.

Figure 2 indicates the CSR of 10% oil-containing soil is between 0.2 and 0.3. The CSR is about 0.5 to 0.6 for pure sand. If the stabilizer, CMC was added to the soil, and the amount of the stabilizer is between 1.0 and 2.0%. The results show the stabilizer did restore the CSR back to the pure sand level or even slightly higher than the value of pure sand. Figure 3 also presents the similar trend. Figure 4 shows the oil-containing sand with CSR between 0.15 and 0.25. However, the pure sand possesses the CSR between 0.33 and 0.38. Obviously, the stabilizer work more efficiently on the soil confined using lower stresses, such as 50 and 100 kPa. Thus, the results imply this method is suitable for being used in reinforcing the soil close to the surface.

Table 1. The relationship between earthquake magnitude and modification factor

Earthquake Magnitude M	Equivalent Number of Cyclic cycles	Modification factor γ_m*
8.5	26	0.89
7.5	15	1.00
6.75	10	1.13
6.00	5-6	1.32
5.25	2-3	1.50

$$* \quad \gamma_m = \frac{\tau_{avg}/\sigma_m \ (M = designed)}{\tau_{avg}/\sigma_m (M = 7.5)}$$

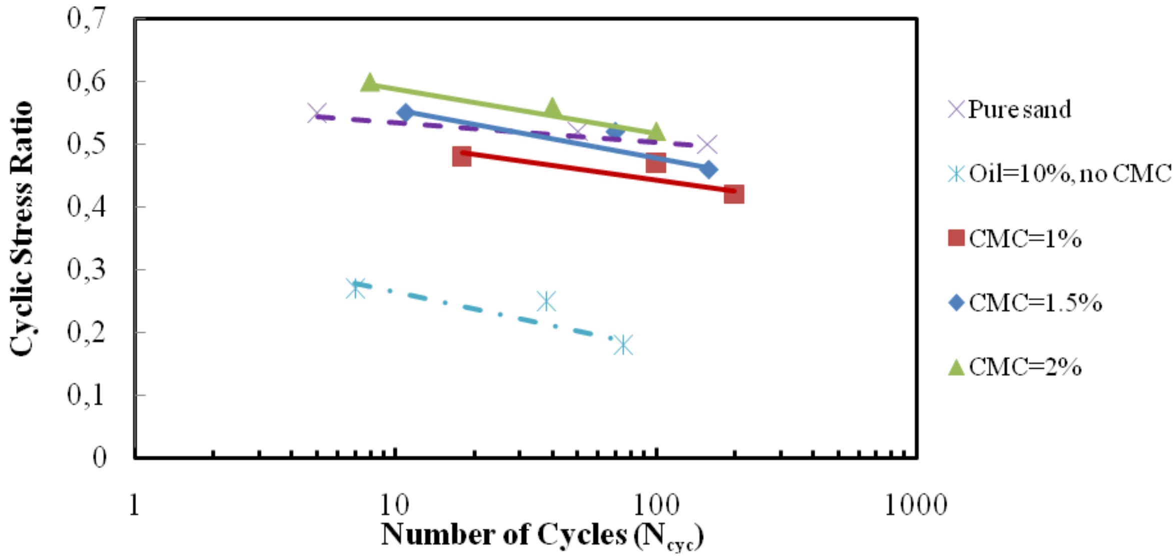

Figure 2. Cyclic stress ratio versus Number of cycles ($\sigma'_3 = 50kPa$, D_r=45%)

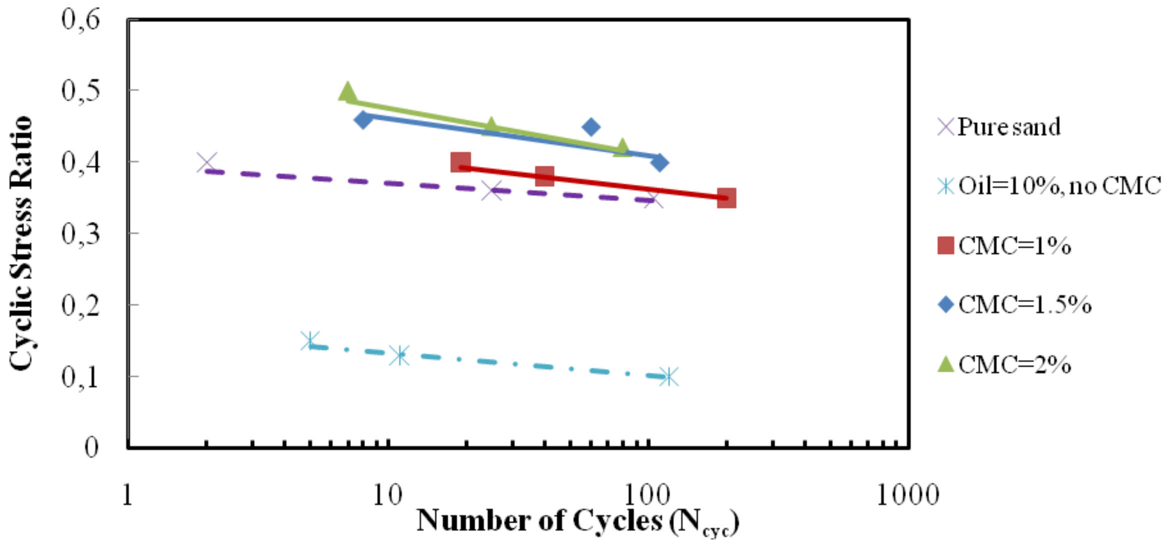

Figure 3. Cyclic stress ratio versus Number of cycles ($\sigma'_3 = 100kPa$, D_r=45%)

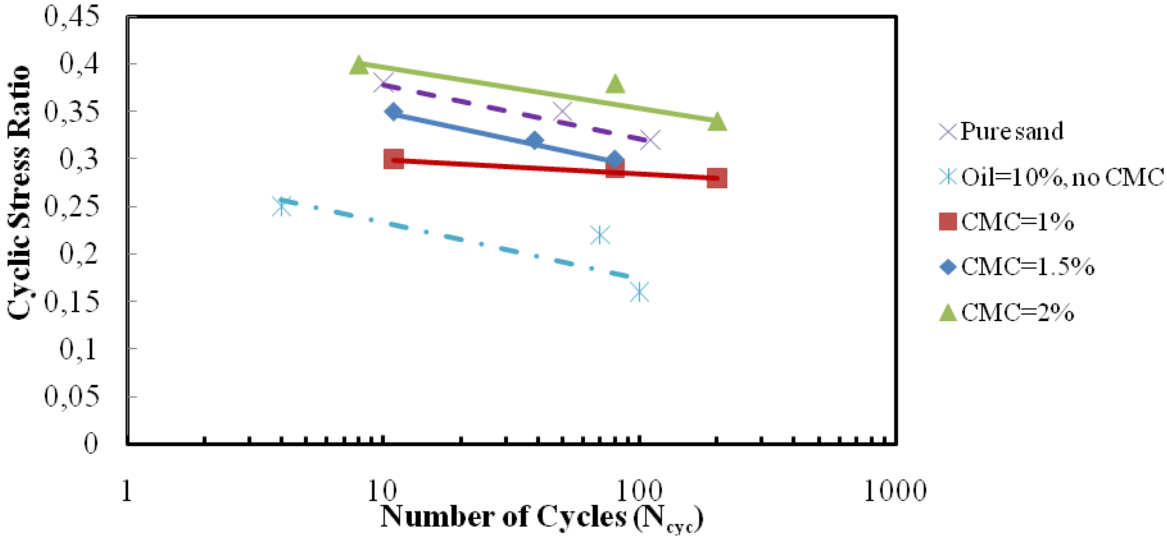

Figure 4. Cyclic stress ratio versus Number of cycles ($\sigma'_3 = 150kPa$, D_r=45%)

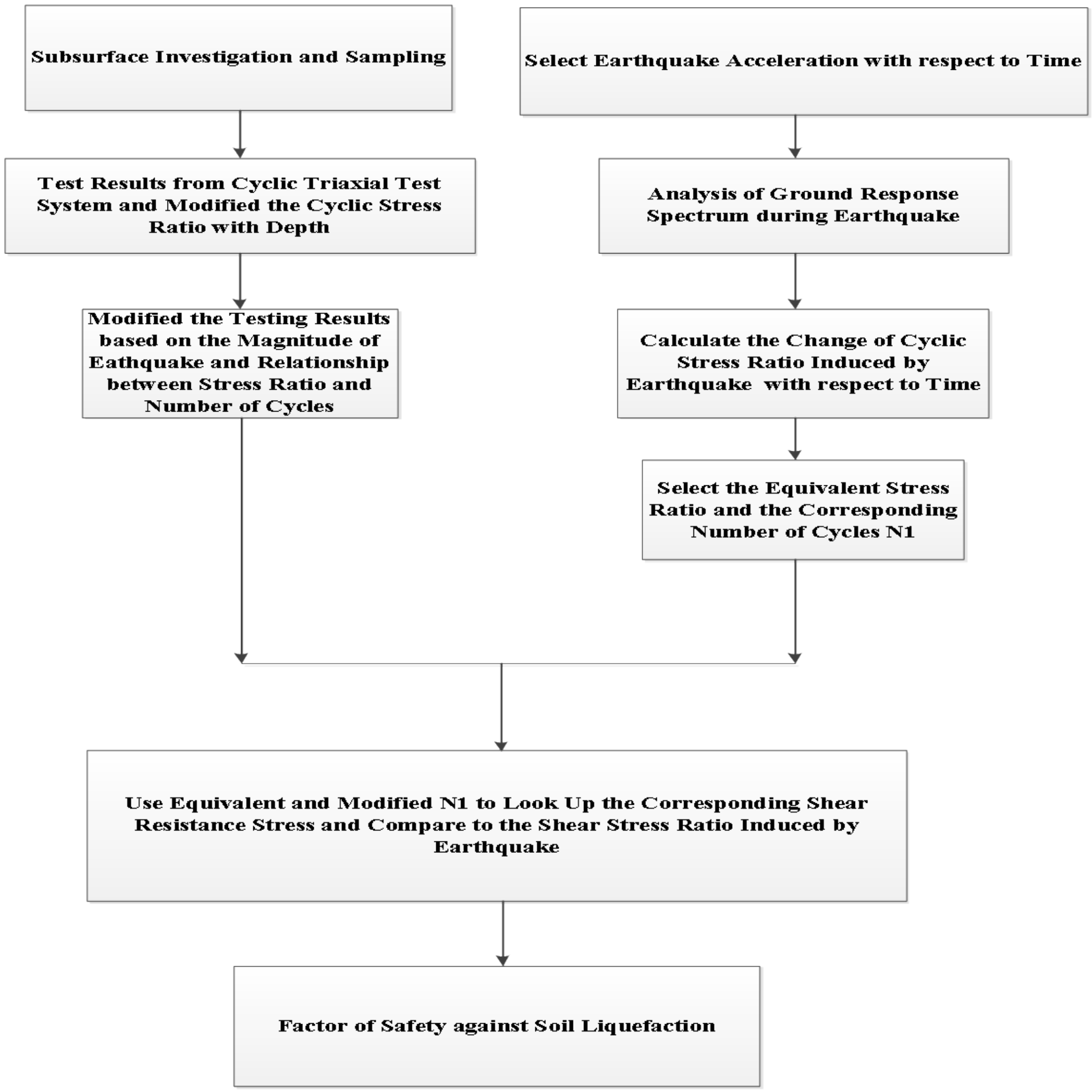

Figure 5. The determination of cyclic stress levels causing liquefaction from laboratory test data

5 SUMMARY AND CONCLUSIONS

The evaluation of liquefaction potential of oil-containing sand is based on the experimental results of cyclic triaxial tests. By making some reasonable assumptions in the tests, several conclusions can be made as follows.

(1) The dynamic strength of oil-containing sand is lowered at 40-60% compared to the pure sand in the same area in terms of CSR if the oil added 10% in the pure sand.
(2) By adding CMC chemical stabilizer into the oil-containing sand, the dynamic strength and the liquefaction resistance will increase even higher than the pure sand if the CMC stabilizer is added more than 1%.
(3) CMC stabilizer was found to increase the liquefaction resistance effectively. Accordingly, the site is not suitable for using some other ground improvement methods can adopt the proposed method to add about 1%-2% of CMC to increase the strength of sandy soil, the bearing capacity and the liquefaction resistance.
(4) In considering to use CMC as the stabilizer to improve the ground, the cost is also the important factor. To make the CMC stabilization as the economical method, the use of CMC stabilizer has to be controlled below 2%. Otherwise, the cost of ground improvement will increase and become uneconomical.

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