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Assessment of liquefaction potential for a silty sand in Central Western Taiwan

Evaluation du potentiel de liquéfaction d'un sable vaseux au centre ouest

A.B. Huang, Y.T. Huang & F.J. Ho
Department of Civil Engineering, National Chiao Tung University, Hsin Chu, Taiwan

ABSTRACT
The Chi Chi earthquake of September 21, 1999 triggered extensive soil liquefaction in silty sand deposits in Central Western Taiwan. The post Chi Chi earthquake studies indicated that the fines content adjustments according to the simplified procedure could cause rather inconsistent results amongst various assessment methods. The authors performed a series of cone penetration chamber calibration tests and cyclic triaxial tests on remolded Mai Liao Sand (MLS) specimens, with various fines contents and densities. The triaxial cell was equipped with bender elements and shear wave velocity (V_s) was measured prior to the cyclic shearing test. With these data, the authors were able to calibrate the correlations among CRR, cone tip resistance (q_c) and V_s for MLS. A test site was developed in Yuan Lin County where standard penetration test (SPT), seismic piezocone and field V_s measurements were performed and low disturbance silty sand samples using a Laval sampler were taken. A series of cyclic triaxial tests were conducted on the Laval samples with V_s measurements using bender elements. These field and laboratory test results were used to validate the correlations among CRR, q_c and V_s from calibration tests and the simplified procedure typically used in liquefaction potential assessment. This paper describes the laboratory calibration tests on MLS, results from Yuan Lin test site studies and discusses their implications in the assessment of liquefaction potential for the silty sand in this region.

RÉSUMÉ
Le tremblement de terre de Chi Chi du 21 Septembre, 1999 a déclenché considérablement la liquéfaction du sable à l'ouest centrale de Taïwan. L'étude de la poste de tremblement de terre de Chi Chi a indiquée que avec les ajustements de contenu fin d'après la procédure existée peuvent causer plutôt les résultats inconsistants parmi les méthodes de l'évaluation variée. Les études existées n'ont pas conduit à consensus comme si les fins peuvent augmenter ou diminuer la résistance cyclique de sable. Les auteurs exécutent une série d'essai de CPT et les essais triaxiales sur l'échantillon de sable de Mai Liao (MLS), avec les densités et contenus fins variés. L cellule tiaxiale a équipée avec les éléments centreuses et V_s a mesurée pour tous les échantillons MLS antérieur à l'essai de cisaillement cyclique. Avec les données, les auteurs ont été capable de calibrer les corrétions parmi CRR, q_c et V_s pour MLS. Une entroit d'essai a développée à la région de Yuan Lin ou SPT, la piezocone seismique et la mesure de terrain V_s ont été exécutés et l'échantillon de sable peu perturbé utilisant une échantillon de Laval sont faites. Une série des essais triaxiales cycliques ont été conduit à l'échantillon de Laval avec les mesures V_s utilisant les éléments centreuses. Les résultats des essais de laboratoire et de terrain ont été utilisés à valider les corrétions parmi CRR, q_c et V_s par les essais calibrés. Cette article déscrit les essais calibrés de la laboratoire sur le MLS, les résultats des études de terrin de Yuan Lin et discut les impications sur l'évaluation de la liquéfaction potentielle pour le sable dans cette région.

1 INTRODUCTION

Field test results such as the N value from standard penetration test (SPT), cone tip resistance (q_c) from cone penetration test (CPT) or shear wave velocity (Vs) have been used to assess the liquefaction potential for sand under the framework of simplified procedure (Youd et al., 2001). The simplified procedure uses an empirical correlation between the cyclic resistance ratio (CRR) and the field test results according to field observations. These CRR correlations basically provide a clean sand base curve and a suggested procedure to account for fines content for sands with fines. The effects of plastic or non-plastic fines on the behavior of sand have been a subject of geotechnical research for many decades. These research activities however, have mostly been limited to cyclic shearing tests on soil samples in laboratory. The laboratory studies have not lead to a consensus as to whether fines can increase or decrease the undrained strength or cyclic resistance of sand as described by Polito (1999). On the other hand, systematic studies on the effects of fines on N, q_c or Vs have rarely been reported. With these drawbacks, Youd et al. (2001) emphasized that the CRR corrections based on fines contents should be used with engineering judgment and caution.

The Chi Chi earthquake (M_W = 7.6) triggered extensive soil liquefaction in Central Western Taiwan. The sand deposit in this region often had significant amounts of fines. When performing back analysis of sand liquefaction potential in this region, the selection of field test method, its CRR correlation and the associated fines content corrections could lead to significantly different results (Huang et al., 2003). It would thus seem desirable to study as to how the fines affect the correlations between the field test results and CRR at least in this region. Mai Liao Sand (MLS) and Yuan Lin Sand (YLS) are typical silty fine sand found in Central Western Taiwan. These sands were used as the subject of the field and laboratory experiments.

2 GEOLOGICAL ORIGIN AND PHYSICAL PROPERTIES OF MLS AND YLS

The origin of both MLS and YLS was the central mountain range that lied on the east side of Taiwan. Weathered sedimentary and metamorphic rocks on steep slopes were eroded by rainfall and transported by rapidly flowing streams before deposition on the west plain, to a thickness of several hundred meters. The process of transportation ground the fractured rock into sand and silt particles. Fig. 1 shows grain size distribution curves of MLS and YLS samples taken from the field. MLS and YLS both had significant amounts of muscovite and chlorite, in addition to quartz. The minimum void ratios (e_{min}) and maximum void ratios (e_{max}) with the fines contents (FC) to be described in this paper, specific gravity (G_s), liquid and plastic limits (L.L. and P.L.) of particles passing No. 200 sieve of MLS and YLS are summarized in Table 1.

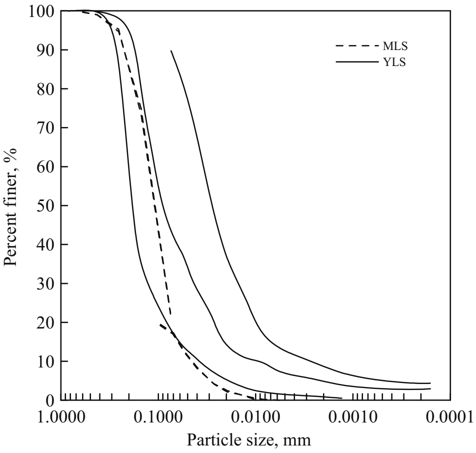

Figure 1. Grain size distribution curves of MLS and YLS.

Table 1. Physical properties of MLS and YLS.

Sand	MLS				YLS		
FC, %	0	15	30	50	18	43	89
e_{min}	0.65	0.59	0.59	0.56	0.85	0.86	1.01
e_{max}	1.13	1.06	1.21	1.31	1.29	1.27	1.69
G_s	2.69 – 2.71				2.72	2.73	2.75
L.L., %	32				21 - 40		
P.L., %	24				8 - 28		

3 LABORATORY CPT CALIBRATION IN MLS

A series of 94 CPT calibration tests were performed in MLS. Four levels of fines contents, FC (0%, 15%, 30% and 50%), three initial relative densities, D_{ro} (50%, 70% and 85%), three levels of effective vertical stress, σ'_v (100, 200 and 300 kPa), and three types of effective horizontal stress, σ'_h to σ'_v ratios, K (= 0.5, 1 and 2) were applied with a few exceptions. The D_{ro} was limited to 50% for CPT in specimens with FC=30%. Most of the K values were 1 for CPT in specimens with FC=50%, while D_{ro} varied from 50% to 70%. The chamber specimen prepared by dry deposition (DD) method had a diameter of 525 mm diameter and a height of 760-815 mm. The chamber was designed to provide constant stress lateral boundary conditions only. Details of the chamber design and its capabilities are referred to Huang et al. (1999).

A comparison of cone tip resistance (q_c) from CPT performed in dry and saturated specimens with fines contents of 15, 30 and 50% are presented in Fig. 2. When FC = 15%, the q_c in dry and saturated specimens agreed within 5%, after reaching a penetration depth of 300mm. We can conclude that CPT performed in MLS with fines contents less than 15% may be considered a drained test. Thus, all tests with FC=0% were conducted in dry specimens. When FC = 30%, q_c in a dry specimen could be more than twice the value as in a saturated specimen. When FC = 50%, the q_c in a dry specimen was over three times that in a saturated specimen. It is apparent that as fines content exceeded 30%, the CPT could no longer be considered a drained test. The equation proposed by Fioravante et al. (1991) was used as a framework to establish an empirical equation for the interpretation of CPT in MLS as

$$\frac{q_c}{P_{a2}} = C_0 \times \left[\frac{\sigma'_v}{P_a}\right]^{C_1} \times \left[\frac{\sigma'_h}{P_a}\right]^{C_2} \times \exp[C_3 \times e] \qquad (1)$$

where

P_a = one atmosphere in the same units as σ'_v
P_{a2} = one atmosphere in the same units as q_c
e = void ratio after specimen consolidation

C_0, C_1, C_2, and C_3 are coefficients to be determined by matching Eq (1) to the CPT data through a regression analysis. Table 2 summarizes the coefficients derived from the regression analysis. A separate set of coefficients was computed for the CPT in specimens with different fines contents. The minimum coefficient of correlation (ρ) between the test values and those computed by Eq (1) is 0.93 as shown in Table 2.
Rearranging Eq (1) so that,

$$C_0 \times [K]^{C_2} \times \exp[C_3 \times e_c] = \left[\frac{q_c}{P_{a2}}\right]\left[\frac{P_a}{\sigma'_v}\right]^{C_1+C_2} = q_{c1N} \qquad (2)$$

where q_{c1N} is the q_c normalized to σ'_v of 100 kPa. C_0 is much larger than C_1, suggesting that σ'_h is a more significant contributing factor to q_c than σ'_v. Table 2 shows that the stress exponent (n) or (C_1+ C_2) increased from 0.45 to 0.80 as the fines contents changed from 0 to 50%. This trend is consistent with that reported by Olsen and Malone (1988). The absolute values of C_0 and C_3 decrease with the fines content. This phenomenon is consistent with the fact that as the fines content increases, the sand becomes less dilatant (or more compressible), and thus offers less resistance to cone penetration. In the case when fines content reached 30%, the cone penetration became partially drained and the cone penetration induced pore pressure was significant enough to result in much reduced tip resistance.

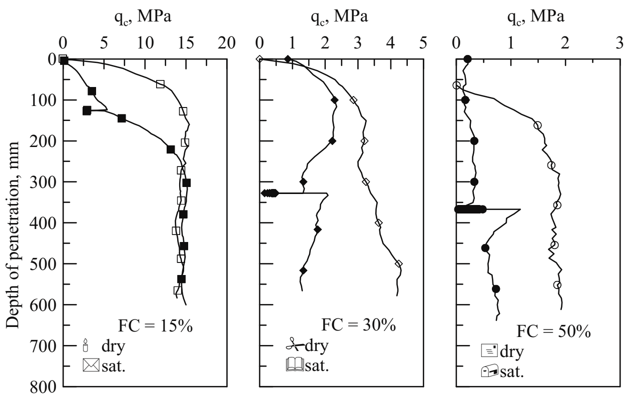

Figure 2. CPT in MLS with different fines contents.

Table 2. Coefficients of Eq (1).

FC, %	C_0	C_1	C_2	C_3	ρ
0	383	0.03	0.42	-2.02	0.94
15	236	0.23	0.44	-1.63	0.96
30	26	0.02	0.77	-1.04	0.95
50	316	0.69	0.11	-6.05	0.93

4 LAVAL SAMPLING AND FIELD TESTS IN YLS

Konrad et al. (1995) reported their success in obtaining undisturbed silty sand samples form below the ground water table without freezing. A 200mm diameter and 500 high sample could be obtained with the Laval Sampler. In order to prevent soil structure damage during transportation for sand with low fines content, Konrad et al. (1995) developed a method to freeze the Laval sample (LS) above ground. The soil, while remained in the sampling tube, was gradually frozen from top of the sample using dry ice, in approximately 24 hours. Bottom drainage was provided to release pore water due to volume expansion during freezing.

The LS along with a series of in situ tests that included SPT, seismic piezocone, and P-S logging were performed at a test site in Yuan Lin Township of Chang Hua County. The boreholes and test locations were distributed within a diameter of 10m. Fig. 3 describes the soil profiles obtained from these series of sampling/in situ tests. Properties of the Laval samples are shown in Table 3.

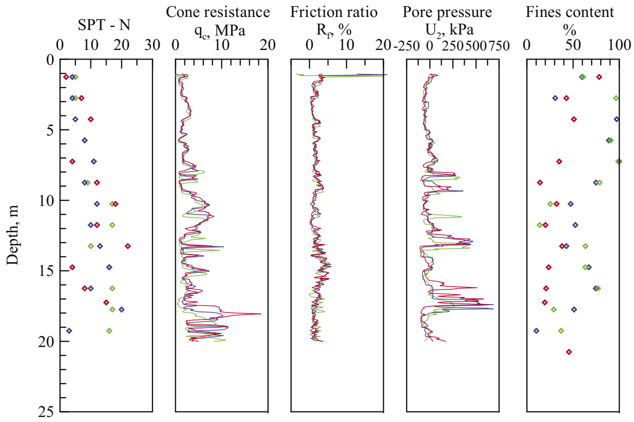

Figure 3. Profiles of test results at the Yuan Lin test site

Table 3. Summary of Laval samples.

Bore hole	LS-1			LS-2			LS-3		
Dep. m	3.3 - 3.8	6.1 - 6.6	10.8 - 11.3	3.5 - 4.1	9.0 - 9.5	10.9 - 11.4	3.6 - 4.1	5.9 - 6.4	11.0 - 11.4
FC, %	43	91	20	31	75	48	43	89	18
L.L.	21	40	25	24	26	22	21	31	25
P.L.	14	28	14	12	16	8	14	19	14

5 LABORATORY MEASUREMENTS OF CRR AND V_S

The CRR were measured using stress controlled cyclic triaxial tests where the soil specimen was consolidated under an isotropic effective confining stress σ'_c and then subjected to a cyclic deviator stress, σ_d in axial direction. Specimens used included undisturbed Laval samples from Yuan Lin and MLS samples reconstituted by moist tamping (MT). The CRR measurements were conducted with σ'_c = 100 and 200 kPa, where we have the most interest in soil liquefaction potential assessment. CRR is defined as the $\sigma_d /2\sigma'_c$ that produces an axial strain of 5% in double amplitude in 15 cycles (N_c) of uniform load application. A back pressure of 300 kPa was used in all the cyclic triaxial tests. The top cap and pedestal of the triaxial cells were equipped with bender elements. The shear wave velocity, V_s was measured using the bender elements, prior to the cyclic triaxial test. Because of the high compressibility of MLS and YLS, the e value after soil consolidation was used in analyzing the test data.

Upon cyclic triaxial test on undisturbed LS, the sample was dismantled to make reconstituted specimens. For the YLS, reconstituted specimens were made following the MT and water sedimentation (WS) methods. Fig. 4 depicts the cyclic triaxial test results on YLS. The increase of fines content had a tendency to lower the CRR. Available data indicated that undisturbed LS had higher CRR than those of reconstituted specimens. Specimens prepared by MT had higher CRR than those prepared by WS.

The MLS was first sieved through a #200 sieve to separate the fines. The coarse and fine particles were then blended to obtain the desired fines content. The test specimens were created following the MT method. FC of 0, 15 and 30% were used in the cyclic triaxial tests on MLS. The shear velocity was measured using the bender elements in this series of cyclic triaxial tests. Figs. 5 and 6 depict the cyclic triaxial test results on reconstituted MLS. For a given e, the CRR decreased with fines contents as in the case of YLS. Additional tests on MLS reported by Huang et al. (2004) showed that specimens prepared by MT had higher CRR than those in turn by WS and DD. The available tests on MLS indicated that for a given e, the CRR was significantly lower as σ'_c increased from 100 to 200 kPa.

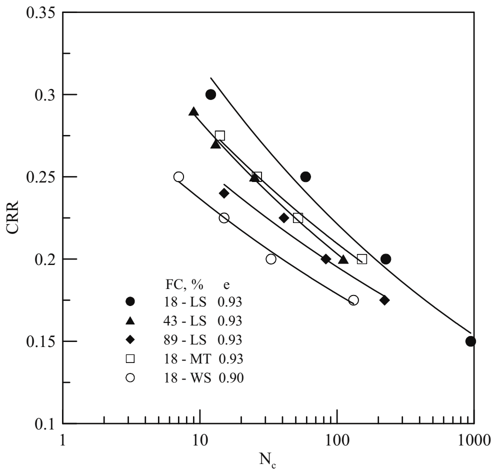

Figure 4. Cyclic resistance of undisturbed YLS.

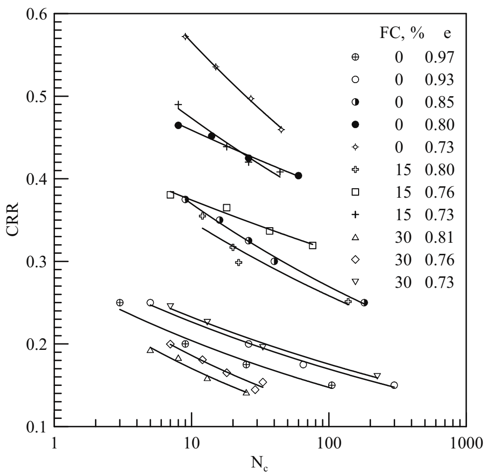

Figure 5. Cyclic resistance of reconstituted MLS under σ'_c of 100 kPa.

6 RELATIONSHIPS AMONG CRR, q_c AND V_S

The laboratory measured q_c and/or V_s values obtained in MLS and YLS were smaller in comparison with those in reconstituted clean, quartz dry sand samples under the same states (Huang et al., 1999: and Huang et al., 2004). These lower values are most likely related to the relatively soft and crushable nature of YLS and MLS, and the effects of fines. For the combinations of FC, e and $\sigma'_h = \sigma'_v$ = 100 and 200 kPa, the corresponding q_{c1N} in MLS was computed according to Eq (2). The CRR values from Figs. 5 and 6, and additional data of cyclic triaxial tests on reconstituted MLS prepared by WS and DD methods reported in Huang et al. (2004) were used to establish the CRR-q_{c1N} and CRR-V_{s1} as shown in Figs. 7 and 8. The triaxial and CPT calibration tests both indicated that under a given density and stress condition, the CRR and q_{c1N} were lower, as FC increased from 0 to 15%. The decrease of CRR from triaxial tests was however, more significant than q_{c1N} as FC increased from 0 to 15%. As a result, the q_{c1N} was only slightly smaller for a given CRR as FC increased from 0 to 15%, this difference is much less significant than that reported by Stark and Olson (1995). Also, for a given CRR, the corresponding q_{c1N} appears to be lower than suggested by Stark and Olson (1995). As FC increased to 30%, q_{c1N} became much smaller. For the limited CRR values from tests on undisturbed YLS Laval samples, the corresponding q_{c1N} were chosen from the field measurements as shown in Fig. 3, at comparable depths where the LS were taken. The results from tests in MLS and YLS both indicated a rather similar CRR- q_{c1N} correlation until fines content exceeded 30%.

The establishment of the relationship between CRR and V_s was straight forward as they both were measured in the same specimen. Fig. 8 shows a plot of CRR versus V_{s1} (V_s normalized to σ'_v of 100 kPa) and their comparison with the correlations proposed by Andrus and Stokoe (2000). For a given CRR, the V_{s1} value from laboratory tests on MLS and YLS specimens were generally smaller than those suggested by Andrus and Stokoe (2000). Unlike CPT however, there was no significant differences in the CRR-V_{s1} correlation as FC increased from 0 to 30%.

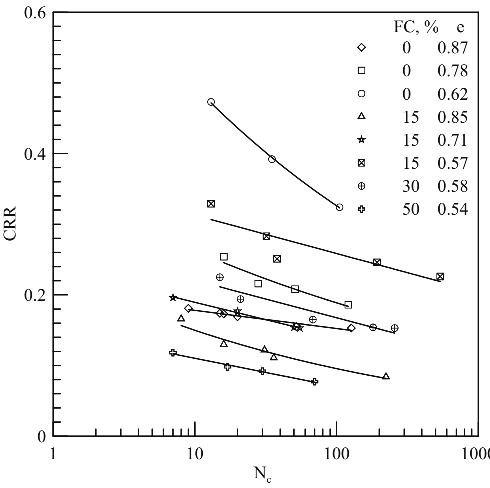

Figure 6. Cyclic resistance of reconstituted MLS under σ'_c of 200 kPa.

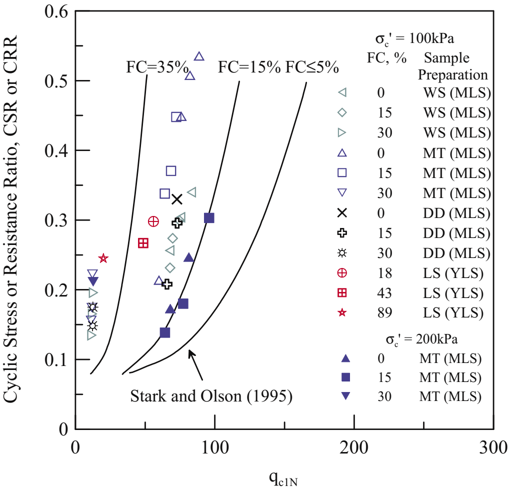

Figure 7. Correlation between CRR and q_{c1N}.

7 CONCLUDING REMARKS

The available data showed that the CRR- q_{c1N} and CRR-V_{s1} correlations developed from the laboratory/field tests on MLS and YLS consistently fell to the left of those proposed by Stark and Olson (1995) and Andrus and Stokoe (2000), respectively. This discrepancy may be due to differences in soil grain characteristics and conservatism rightfully applied in those correlations by Stark and Olson (1995) and Andrus and Stokoe (2000).

Neither CPT nor field shear wave velocity measurement involve soil sampling. Unless soil samples were taken, the amount of fines content would have to be estimated or inferred from empirical soil classification methods in the case of CPT. The amount of adjustment in q_{c1N} or V_{s1} can be very sensitive to fines content according to the commonly used simplified procedures. The high sensitivity coupled with uncertainties in the estimation of fines contents may well be the reasons for inconsistent results in assessing the liquefaction potential in Central Western Taiwan when applying different assessment methods. The data presented in this paper do not support the idea of fines content adjustment in its conventional sense. The fines content and its q_{c1N} adjustment becomes important only when the fines start affecting the drainage condition in CPT. The test data also indicate that there seems to be no need to distinguish the CRR-V_{s1} correlations according to fines content, at least for MLS and YLS.

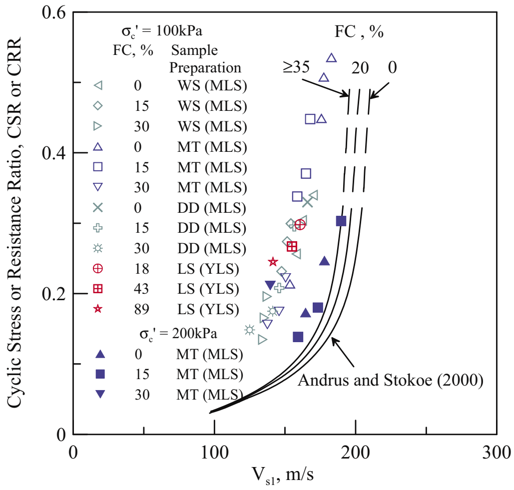

Figure 8. Correlation between CRR and V_{s1}.

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