Evaluation of Cone Penetration Resistance in Loose Silty Sand Using Calibration Chamber

Mohammad Hassan Baziar[1] , Reza Ziaie_Moayed[2]

[1]Professor, College of Civil Engineering, Iran University of Science and Technology, Narmak-Tehran, Iran, Fax: 98-21-7491033, E-mail: Baziar@iust.ac.ir

[2]Assistant Professor, Civil Engineering Department, International University of Imam Khomeini, Ghazvin, Iran

Abstract: *This paper highlights the effect of silt content on cone tip resistance in loose silty sand. In this study, twenty-seven cone penetration tests are performed in saturated silty sand samples with several different silt contents ranging from 10 to 50 percent. The samples are consolidated at three overburden stresses including 100, 200 and 300 kPa. It is shown that, as the silt content increases, the cone tip resistance decreases. In high percent of silt (30-50%), the cone tip resistance decreases more gently compared with low percent of silt (0-30%). It is also concluded that the method proposed by Olsen (1997) for stress normalization of cone tip resistance compared with the Robertson and Wride (1998) method has better agreement with the obtained results. To evaluate liquefaction potential of loose silty sand, the method presented by Robertson and Wride (1998) is also studied. The results showed that the use of Robertson and Wride (1998) method to estimate the fine content from CPT data causes some uncertainty especially for high silt content (FC>30%).*

Keywords: *Cone tip resistance, Silty sand, Stress normalization, Liquefaction*

1-Introduction

For soils such as silty sands, limited studies have been accomplished toward improving the interpretation of in-situ test results (Filho, 1982; Peterson, 1988, Rahardjo et. al., 1995). In pervious investigations, only silty sands with specific silt content have been tested. For example, Filho (1982) examined a well-graded medium to fine silty sand obtained from North Sea. Rahardijo et al. (1995) used Yatesville silty sand from the site of the Yatesville Lake – dam on Blaine Creek, which contained approximately 40% non-plastic fines. In other words, in previous studies, a complete set of laboratory tests has not been conducted to evaluate the influence of different silt contents on CPT results.

Estimating the liquefaction resistance of non-clean sands using cone penetration resistance based techniques can be accomplished by three methods:

- Calculated equivalent clean sand (Seed et al, 1983; Ishihara, 1985; Seed and DeAlba, 1986; Robertson and Wride, 1998).

- The chart-based solution in terms of a measured soil index (Olsen, 1997).

- Direct correlation to field case histories (Shibata and Teparaksa, 1988; Stark and Olson, 1995, Baziar and Ziaie-Moayed, 1998).

It is important to note that the above approaches are sensitive to the amount of silt content and its effect on CPT results. The purpose of this research is to evaluate the influence of silt content on cone penetration resistance in loose silty sand mixtures in calibration chamber and then to verify the existing methods to determine liquefaction potential of loose silty sand soils.

2-Test ethod and equipment

2.1-Calibration Chamber

Calibration chambers have been used to help in the process of developing correlations between in-situ test results and different soil parameters. Since its early development in the late 1960s, the calibration chamber has been an important research tool in establishing a base for interpretation of cone penetration results in sand.

The testing chamber is consisted basically of a rigid thick walled steel cylinder of 0.76-m internal diameter and 1.50-m height, with removable top and bottom plates. The basic philosophies for the design of this calibration chamber are as follows:

- To model a perfectly rigid lateral wall condition.

- The soil specimen should be large enough to minimize boundary effects without the need for sophisticated lateral boundary controls.

Given the diameter of a standard cone, 3.57 cm (ASTM D5778), the Rd for IUST calibration chamber is about 21. This implies that with using a standard cone in loose sandy soil, there will be no effect of boundary conditions for this calibration chamber. Also, the length of specimen should be as long as possible to minimize the effect of upper and lower boundaries. However, other practical factors such as cost effects led to choose the height of chamber to be 1.5 m.

A rubber membrane cap, forming a flexible diaphragm is used to apply load to the top of the sample, simulating a big odeometer device and producing samples with different stress histories. The main part of the chamber is a 1.0-cm thick cylindrical shell bolted to the circular top and bottom plates with 2.5-cm thickness.

2.2- Cone Penetrometer

The standard piezocone is inserted into the chamber by a hydraulic system. Standard piezocone used in this investigation has 10 cm2 projected tip area and a 150-cm2-friction sleeve area. In this penetrometer, the friction sleeve is sited immediately behind the cone tip. The filter element to record pore water pressure is located immediately behind the cone tip. The piezocone is advanced through soil at a constant rate of 20 mm/sec. Three sets of data including cone tip resistance, friction resistance and pore water pressure can be recorded continuously during sounding in each 1 cm of depth.

2.3- Soil Sample

Approximately 60 tons of Tello clean fine sand from North of Tehran was acquired for this research. This alluvial soil is fine clean sand without any clay or silt particle and has specific gravity of 2.6. The properties of the soil used during this study are shown in Table (1). Typical gradation curves of this material are shown in Fig (1). The sand is a rounded to sub-angular fine grained quartz sand with D50=0.4 mm and Cu=3.0. In order to determine the influence of silt content on cone tip resistance, the pure silt was obtained from grinding of Tello fine sand. Approximately 10 tons of silt material was obtained to prepare different mixtures of silt

TABLE 1. Properties of Tested Materials

Material	D_{50} (mm)	C_U	F.C.(%)	e_{min}	e_{max}
Tello Clean	0.4	30	0	0.746	1.05
Ts-10	0.38	5.6	10	0.625	1.0
Ts-15	0.35	7.1	15	0.608	0.99
Ts-20	0.34	7.5	20	0.594	0.97
Ts-25	0.33	7.45	25	0.584	0.94
Ts-30	0.32	7.4	30	0.572	0.92
Ts-35	0.28	7.14	35	0.535	0.91
Ts-40	0.24	6.88	40	0.52	0.895
Ts-50	0.075	5.53	50	0.485	0.875

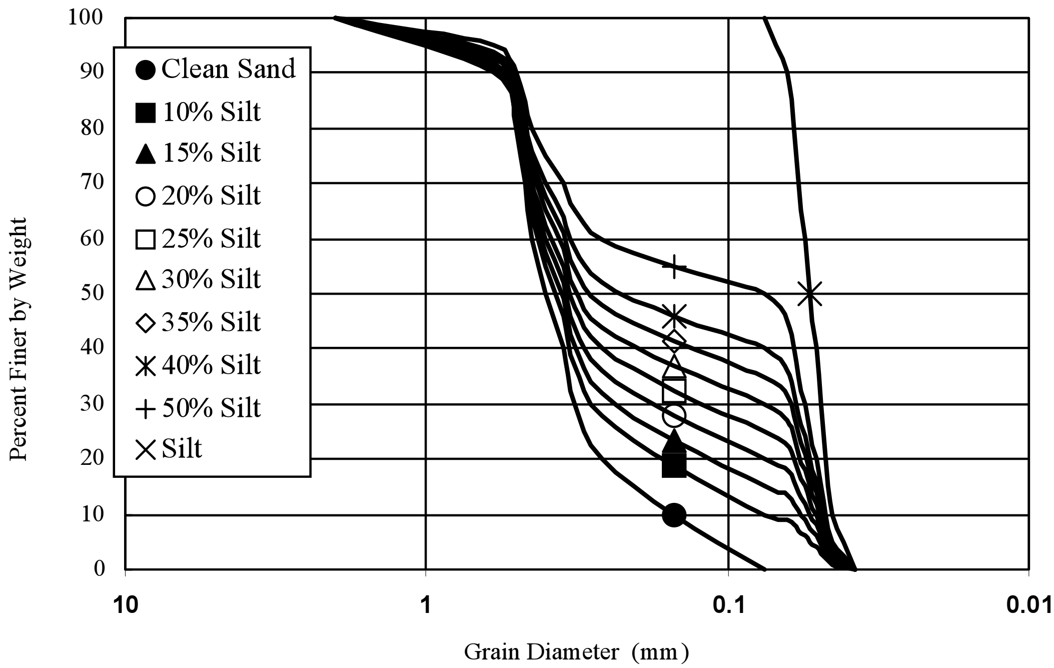

Fig. 1. Grain Size Distribution curve of Tello Sand

TABLE 2. CPT Results

Test No.	Type of Material	Silt Content	σ' (kPa)	q_c (MPa)	u_e (kPa)	f_s (kPa)	e
1	Clean Sand	0%	100	1.6	0	2	1.0
2			200	3.5	0	3	0.98
3			300	4	0	4	0.975
4	Silty Sand	10%	100	1.4	14	1	0.966
5			200	3	15	5	0.958
6			300	3.4	16	13	0.953
7		15%	100	1.3	20	2	0.956
8			200	2.6	22	8	0.946
9			300	3	25	15	0.941
10		20%	100	1.2	24	3	0.923
11			200	2.2	25	10	0.911
12			300	2.8	30	20	0.905
13		25%	100	0.95	26	4	0.912
14			200	1.75	28	16	0.895
15			300	2.6	32	30	0.893
16		30%	100	0.8	30	4	0.888
17			200	1.45	32	23	0.874
18			300	2.5	35	40	0.881
19		35%	100	0.7	32	7	0.873
20			200	1.25	38	26	0.849
21			300	2.45	44	52	0.836
22		40%	100	0.65	35	10	0.85
23			200	1.2	45	27	0.83
24			300	2.4	50	60	0.82
25		50%	100	0.6	60	7	0.832
26			200	1.1	80	20	0.796
27			300	2.2	90	60	0.778

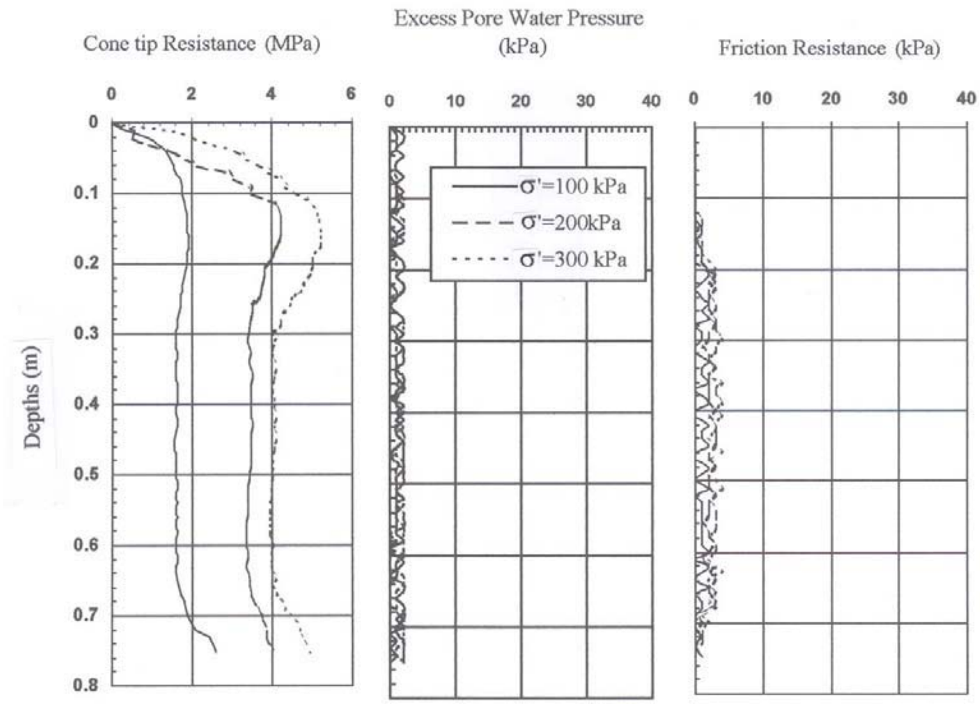

Fig. 2. Typical CPT Results in Clean Sand Specimen

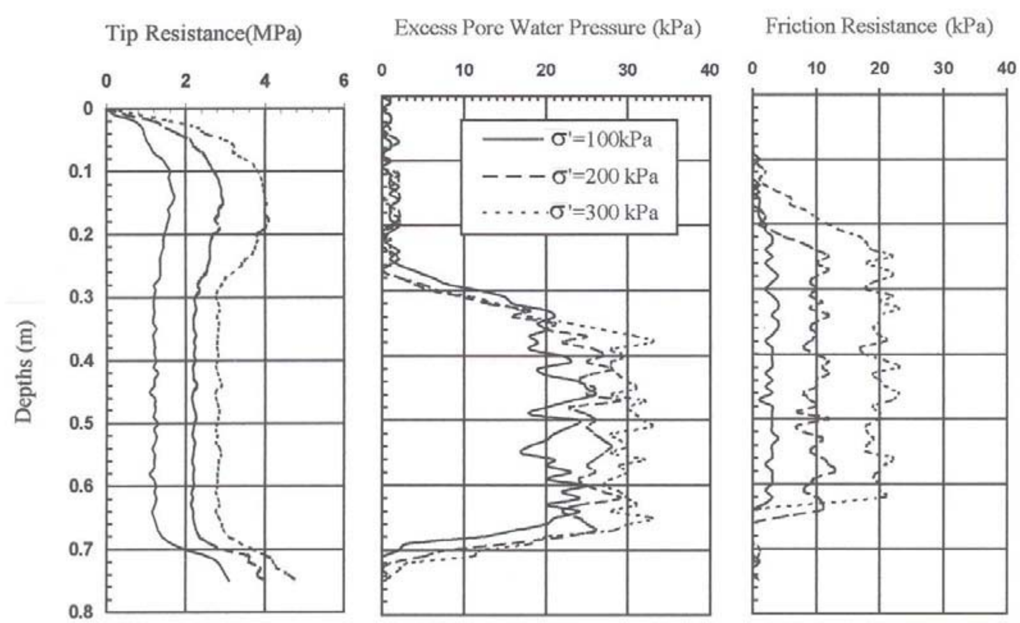

Fig. 3. Typical CPT Results in Silty sand Specimen (15% silt content)

and sand. The soil samples were constructed by dry pouring from small distance such that no segregation of the particles occurred and very loose sample were built.

2.4-Experiment Procedures

All the tests reported in this research were conducted in five stages including: sample preparation, saturation, consolidation, CPT sounding, and evacuation (Ziaie-Moayed, 2001).

3-Test Results

A total of twenty-seven cone penetration tests were performed in calibration chamber including three samples of clean sand and twenty-four samples of silty sand. Table (2) presents summary of the CPT results, obtained in this study.

Fig. 2 shows typical results from continuous penetration with pore water pressure measurement in normally consolidated clean sand samples at three different consolidation pressures. Fig. 3 indicates the same values corresponding to a silty sand sample containing 15 percent of silt. It should be noted that in each sample, there is a 20-cm top and 80 cm bottom filters and the total length of soil sample is about 50 cm. This height of tested sample (50-cm) is obtained from test results to achieve the homogeny condition of tip resistance distribution along the sample depths. It can be seen that from the top of specimen, the qc value increases and reaches to a maximum value in top filter zone area, then reduces and remains constant along the soil sample. This pattern is observed in clean and silty sand samples. At the end, when the cone tip reaches to bottom filter (depth 70 cm), the cone tip resistance increases again.

Excess pore water pressure is approximately zero in the top filter zone (20 cm of upper part of each sample). In clean sand samples, the excess pore water pressure is almost zero, while in silty sand samples, excess pore water pressure grows up and reaches to a constant value in the main part of sample and then reduces to zero in bottom filter zone (depth 70 cm).

The friction resistance values are negligible in clean sand specimens. However, a large amount of friction resistance is recorded during sounding in silty sand samples.

4- Discussion

4-1- Effect of Confining Pressure on q_c

Results of laboratory penetration tests show the influence of confining pressure on tip resistance. Due to obtained results, it is concluded that, the cone tip resistance increases with increasing the confining pressure in clean sand, as it would be expected. In silty sand samples, the cone tip resistance also increases when the confining pressure increases. It is clearly shown that the confining pressure has a major effect on qc as previously was reported (Robertson and Wride 1998, Olsen 1997).

There are numerous techniques for stress normalization of CPT measurements. These stress normalization can be divided into the following categories (Olsen, 1997):

1)- Linear relationship
2)- Constant exponent
3)- Variable stress exponent

4)- Stress focus technique

The stress focus theory uses a variable stress exponent for stress normalization as below:

$$q_{c1}=(q_c - \sigma_v)/(\sigma'_v)^c \qquad (1)$$

Where c is stress exponent dependent on soil type and relative strength level. In this technique, the stress exponent can be estimated directly from CPT results.

Robertson and Wride (1998) proposed the following equation for stress normalization of CPT penetration resistance:

$$Q=[(q_c-\sigma_v)/P_a]*[P_a/\sigma'_v]^n \qquad (2)$$

where n = stress exponent.

They recommended that the stress exponent should be selected based on soil type and soil behavior type index (Ic):

$$I_c=[(3.47-\log Q)^2 + (\log F + 1.22)^2]^{0.5} \qquad (3)$$

where Q is the normalized CPT penetration resistance and F is the normalized friction ratio.

In the present study, CPT tests were performed in three level of vertical effective stress including 100, 200 and 300 kPa. The two recent stress normalization methods, proposed by Olsen (1997) and Robertson and Wride (1998), were used and compared with obtained results.

Figure (4) presents the normalized cone tip resistance values obtained based on above two methods and are compared with original cone tip resistance that resulted from CPT sounding in 100 kPa effective stress level. As shown in Figure (4), the normalized cone tip resistance values obtained from 200 kPa data, based on Olsen (1997) method, is in good agreement with the obtained data. However, the normalized cone tip resistance values that resulted from 200 kPa data using the Robertson and Wride (1998) method have some differences with the obtained data, especially in low percent of silt (0-15%). It can be concluded that, in this case, selection of n=0.5 in very loose silty sand with low percentage of silt (0-15%), causes considerable errors. Therefore, it is recommended to use the equation proposed by Olsen (1997) to normalize the cone tip resistance for the overburden effective stress. Also it can be seen that, in Figure (4), the normalized cone tip resistance values, which are calculated based on these two methods for 300 kPa confining pressure, have low compatibility with the obtained data. The existing differences between obtained data and normalized values in 300 kPa can be resulted from the validity of the above normalization methods up to the range of 200 kPa effective overburden stress. In other words, in this equation the proposed normalization method has a good accuracy in the range of 100 to 200 kPa of effective overburden pressure.

4-2- Effect of Silt Content on Cone Tip Resistance

Many researchers have studied the CPT results in silty sand soils (Robertson and Campanella, 1985, Seed and DeAlba, 1986, Stark and Olsen, 1995, Robertson and Fear, 1995, Robertson and Wride, 1998, Olsen, 1997, Rahardjo et al, 1995).

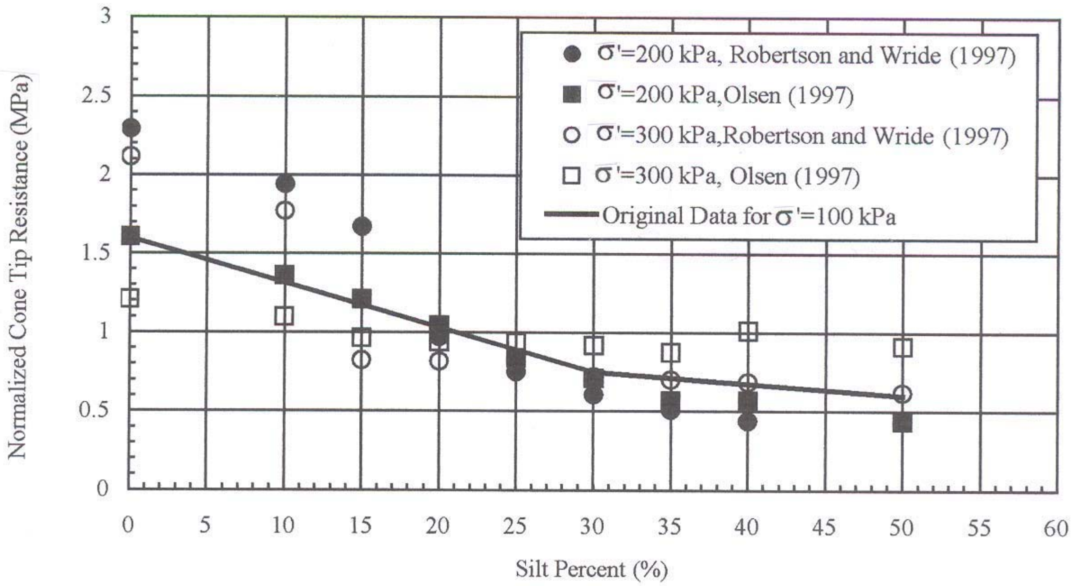

Fig. 4. Normalized Cone Tip Resistance for Different Silt Contents

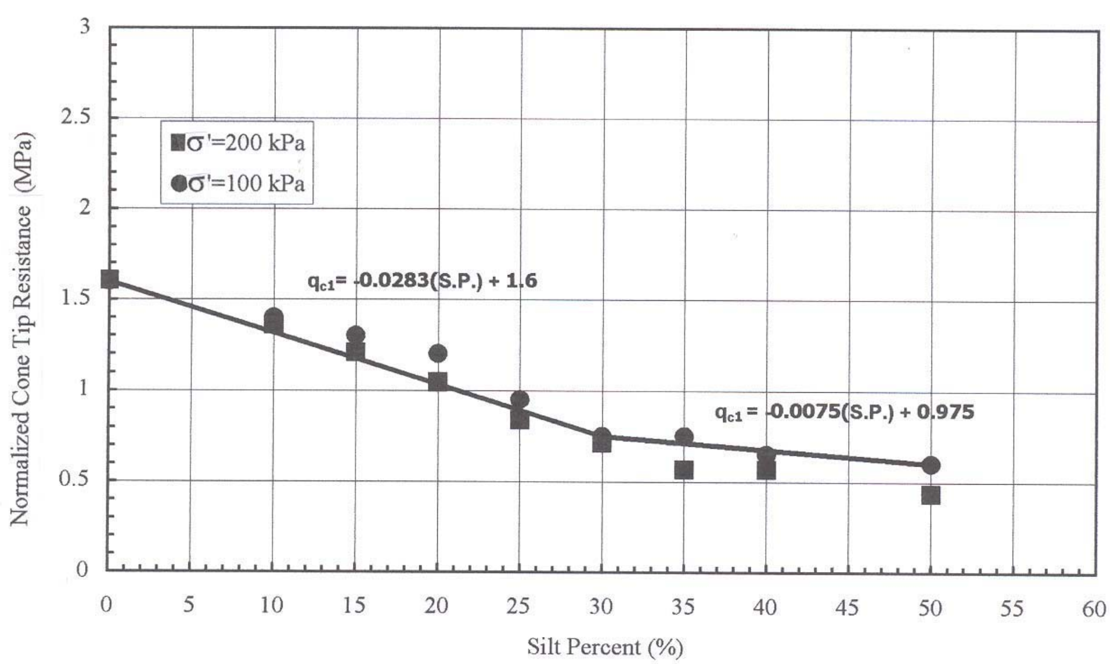

Fig. 5. Normalized Cone Tip Resistance Versus Silt Content

Robertson and Campanella (1985) emphasized that cone penetration in fine-grained soils often make under undrained or partially drained condition and dynamic pore pressure can be generated. They also resulted that since the compressibility of silty sands is typically higher than that of clean sands, silty sand may have tip resistance lower than that of clean sand.

Stark and Olsen (1995) anticipated that, during penetration, the fines may cause partially undrained condition, which can lead to decrease in CPT tip resistance value as compared with a clean sand of equal relative density. Robertson and Wride (1998) found that the CPT penetration resistance in silty sand is smaller due to greater compressibility and decreased permeability of silty sands.

Value of normalized cone tip resistance for confining pressures of 100 and 200 kPa versus fines content is presented in Fig (5). The relations shown in Figure (5), which is proposed to determine the normalized cone tip resistance of loose silty sand in term of fines content for confining pressures of 100 and 200 kPa, can be represented as below:

$$q_{c1N} = -0.0283\ (S.P.) + (q_{c1N})_{cs} \quad \text{For } 0 < S.P.\ (\%) < 30\%$$

$$q_{c1N} = -0.0075\ (S.P.) - 0.625 + (q_{c1N})_{cs} \quad \text{For } 30 < S.P.\ (\%) < 50\% \tag{4}$$

In this Figure, it is also seen that the line presenting the decrease in q_c has two different slopes. It is interesting that 30 percent silt content is the margin of change in slopes of above lines. In high percentage of silt (30-50%), the cone tip resistance decreases more gently compared with low percent of silt (0-30%). The general trend of decrease in qc with increase of silt content can be explained by the following hypothesis.

In the low percentage of silt (0-30%), system acts similar to a coarse granular matrix. Behavior of soil sample in this case is related to contacts of coarse grain and quantified by inter-granular void ratio. Increasing the silt content in the range of 0% to 30%, the contact between sand particles decreases and hence the qc decreases. In high percent of silt (30%-50%), system acts similar to a fine matrix with floating coarse grains. In this case, the behavior of soil sample is related to shear strength of fine particles. With the presence of silt in saturated soil, the CPT sounding is performed in partially drained condition. With more increase of silt content, the condition changes to undrained with generation of pore water pressure. As the silt content increases, the generated excess pore water pressure increases, the effective stress decreases, and hence, the shear strength of sample and cone tip resistance decreases. However, in this situation, the consolidation behavior of system increases and the global void ratio decreases. Therefore as the silt content increases, the contact of soil particle increases. These two factors, affecting in opposite direction, control the cone tip resistance, and as a result in high percent of silt, the cone tip resistance decreases more gently compared with low percent of silt.

5- Liquifaction Resistance of Silty Sand

The fines content of non-clean sand is an important ingredient for cone resistance-based techniques to estimate liquefaction resistance. Fines content can be either 1) measured from samples taken from nearby boreholes or 2) estimated using CPT- based techniques. In recent years, new correlations have been proposed to determine fines contents directly from CPT data (Robertson and Wride, 1998 and Olsen, 1997). Robertson and Fear (1995) presented an equation to obtain the equivalent clean sand normalized CPT penetration resistance, (qc1n) cs, as a function of both measured penetration resistance, qc1n, and grain characteristics of the soil as follows:

$$(q_{c1n})_{cs} = (K_{cpt}) * q_{c1n} \quad (5)$$

where K_{cpt} is a correction factor and is a function of grain characteristics of the soil. They presented a chart to determine the K_c factor from fines content. However, the recommended procedure was to determine the fines content of the soil by sampling.

Robertson and Wride (1998) suggested a method for estimating fines content based on CPT data. They defined the soil behavior type index (Ic) as Equation 3. They pointed out that the proposed correlation between CPT soil behavior index (Ic) and apparent fines content is an approximation, since the CPT responds to many other factors affecting soil behavior such as soil plasticity, mineralogy, sensitivity and stress history is not included in the correlation. The results obtained by other researchers showed that the determination of fines content of silty sands based on only CPT data might cause some uncertainty (Finn et al., 1993, Larsson et al., 1995).

In this research, the method presented by Robertson and Wride (1998) are verified by means of CPT results obtained from loose silty sand samples. For this purpose, the normalized CPT penetration resistance (Q) and normalized friction ratio (F) were determined for silty sand specimens and then the soil behavior index (Ic) was calculated based on the above correlations. Figure (6) shows the fines content in terms of soil behavior type index. The proposed correlation by Robertson and Wride (1998) is also presented in this Figure.

It is noted that, there are some differences between the predicted equation and the data obtained in this research, especially for high silt percent (FC>30%). It is concluded that, the use of Robertson and Wride (1998) method to estimate the fines content from CPT data in loose silty sand specimens causes some errors. Therefore, it is proposed to use excess pore pressure parameter such as ?u and t50 to determine the fines content from CPT data.

At present, it seems that the proposed method by Robertson and Fear (1995) to evaluate the liquefaction potential of loose silty sand remains suitable. To evaluate this method, the correction factor (Kc) was determined based on obtained results and compared with Robertson and Fear (1995) curve (Fig 7). As shown in this Figure, for 200 kPa confining pressure, there is suitable accordance between proposed curve and obtained results. It should be noted that, since the stress normalization method presented by Robertson and Wride (1998) does not give good accuracy in 100 and 300 kPa confining pressure (Figure 4), only the 200 kPa data is presented in Figure (7).

6-Conclusions

In an attempt to study the cone penetration resistance in silty sand using calibration chamber results and in the light of the experimental evidence, the following conclusions may be drawn:

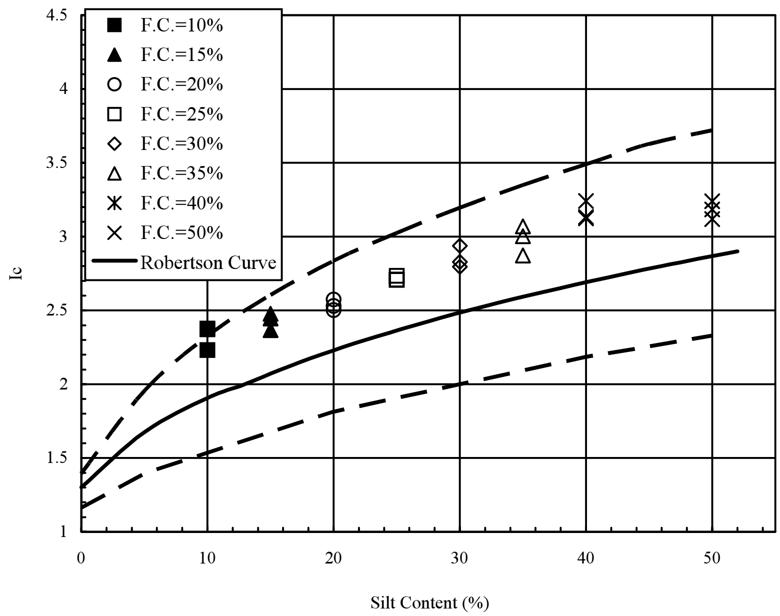

Fig. 6. Silt Content Versus Ic

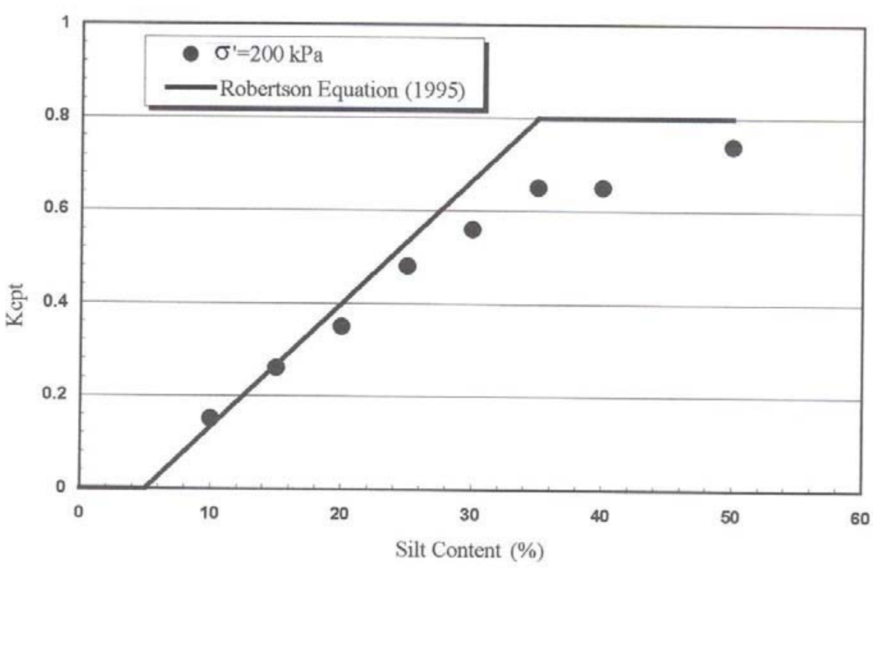

Fig. 7. Kcpt Versus Silt Content

1- The amount of silt content in sand is an important parameter affecting cone tip resistance. As the silt content increases, the cone tip resistance decreases. However, in high percent of silt (30-50%), the cone tip resistance decreases more gently compared with low percent of silt (0-30%).

2- The method proposed by Olsen (1997) for stress normalization of cone tip resistance compared with Robertson and Wride (1998) method has better agreement with the obtained results. Therefore, it is recommended to use the equation proposed by Olsen (1997) to normalize the cone tip resistance for the overburden effective stress in silty sands.

3- To evaluate the liquefaction potential of loose silty sand, the method presented by Robertson and Wride (1998)is also verified. The results showed that, the use of Robertson and Wride (1998) method to estimate the fines content from CPT data causes some uncertainty especially for high silt content (FC>30%). However, at present, it is concluded that the method proposed by Robertson and Fear (1995) to evaluate the liquefaction potential of loose silty sand remains suitable.

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APPENDIX

Notation

The following symbols are used in this paper:

C_u = Uniformity Coefficient ;

D_{50} = Mean Grain Size Diameter (mm) ;

e = Global Void Ratio ;

e_c = Inter-Granular Void Ratio ;

e_f = Inter-Fine Void Ratio ;

F = Normalized Friction Ratio ;

FC = Fine Content (Percent Passing of ASTM Sieve No. 200) ;

I_c = Soil Behavior Type Index ;

K_c = CPT correction Factor (Robertson and Fear, 1995) ;

K_{cpt} = CPT correction Factor (Robertson and Wride, 1998) ;

n = Stress Exponent ;
Pa = Atmospheric Pressure ;

Q = Normalized CPT Penetration Resistance;

q_c = Measured Cone Tip Resistance (MPa) ;

q_{c1n} = Normalized Cone Tip Resistance, Based on Overburden Stress (MPa) ;

$(q_{c1n})_{cs}$ = Equivalent clean sand normalized CPT tip resistance (MPa);

R_d = The Ratio of the Calibration Chamber Diameter to the Cone Penetrometer Diameter

S.P. = Silt Percent

σ_v= Total Normal Overburden Stress (kPa)

σ'_v= Effective Normal Overburden Stress (kPa)

U_e = Excess Pore Water Pressure (kPa)

f_s = Side frictional resistance (kPa)