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LIQUEFACTION POTENTIAL OF SILT

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SUMMARY

A nonplastic silt was tested to study its liquefaction resistance, τ_ℓ, by means of laboratory cyclic triaxial tests and piezocone penetrometer tests in the field. The results were compared with those reported in the literature. The comparison shows that this silt has a lower τ_ℓ than sand and that the laboratory τ_ℓ is much lower than that from the field. The discrepancy is attributed to the role cohesion plays in granular soils. Practical implications on testing silt are discussed.

INTRODUCTION

Increased level of urbanization and energy resource exploration have pushed many construction activities into areas that were avoided in the past because of poor foundation subsoils. Silt is one of the poor foundation materials that present problems to design and construction particularly in zones with earthquake activities. Research is urgently needed to ensure efficient and safe development over these areas.

The objective of this investigation is to evaluate the liquefaction resistance of a nonplastic silt from northern Ontario, Canada. The liquefaction resistance is defined as the shear stress at liquefaction failure. A piezocone penetrometer and a cyclic triaxial device were used for the experimental study. The results are compared with those from the existing literature.

SOIL CHARACTERISTICS

The site is located near Armstrong, a small community in northern Ontario. The subsoil at the site is composed of a 1 m thick layer of muskeg overlying a deposit of silt and traces of sand down to a depth of about 21 m, underlain by a layer of varved clay to about 33 m. Gravel, cobbles and boulders overlie the bedrock located at about 34 m. The present study deals with the silt that has the following characteristics.

Bulk density	20.7 kN/m^3
Maximum void ratio	1.14
Minimum void ratio	0.48
Cohesion	0 kPa
Friction angle	35°
Specific gravity of soil grain	2.72
Grain shape	Subangular to rounded
Plasticity	Nonplastic

The grain size distribution of the silt is shown in Figure 1. The average grain size, D_{50}, is 0.025 mm.

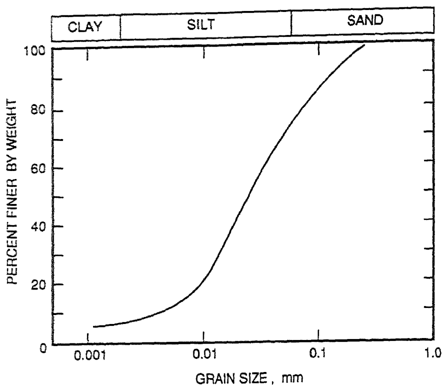

FIGURE 1

AVERAGE GRAIN SIZE DISTRIBUTION

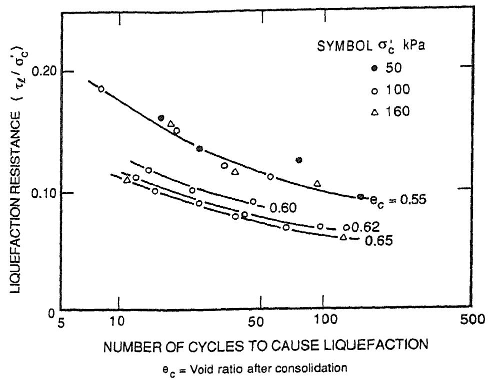

FIGURE 2

LIQUEFACTION RESISTANCE vs NUMBER OF CYCLES TO CAUSE LIQUEFACTION

TEST PROGRAM

The test program included piezocone penetrometer tests at the site, soil sampling by means of a 76.2 mm diameter Osterberg sampler and laboratory cyclic triaxial tests on reconstituted and undisturbed samples.

An electric GMF 50-kN cone penetrometer fitted with a 60°, 10 cm^2 area cone for measuring tip resistance, sleeve friction and pore water pressure was used. The pore pressure was measured through a 4 mm-thick cylindrical porous stone located immediately above the conical tip. The electrical signals from the transducers were read at a rate of one complete set of readings per 1.5 s using a data acquisition unit controlled by a portable computer. The rate of cone penetration was approximately 1 cm/s.

The Osterberg piston sampler has been proven to produce high quality samples of soft, sensitive clay. The outside diameter of the sampling tube is 76.2 mm and the wall of the tube is 1.73 mm thick. 100% recovery of the silt samples was obtained with this equipment. However, some sample disturbance may have been introduced because of difficulty in extruding the samples from the tubes. In this paper, therefore, the term undisturbed sample is used in a nominal sense.

Undrained cyclic shear was applied to reconstituted samples after being isotropically consolidated to different cell pressures (σ_c'). For the undisturbed samples, a constant σ_c' equal to 100 kPa was used.

TEST RESULTS

Laboratory Tests

The responses of the reconstituted and undisturbed samples were very different though both had been consolidated to the same pressure and at about 90% relative density. The reconstituted sample behaved like a loose sand. The axial displacement was small in the early part of the cyclic shear in which the pore pressure increased steadily. As soon as the pore pressure reached about 85% of the consolidation pressure (σ_c'), the displacement suddenly increased. Within several more cycles, the sample liquefied at pore pressure equal to 100% of σ_c' and collapsed. The response of the undisturbed sample during the early part of cyclic loading was similar to that of the reconstituted sample. When the pore pressure reached 80% of σ_c', the axial displacement started to increase more rapidly. The sample, however, did not collapse even well into the stage of the pore pressure being equal to σ_c'. Within this stage the displacement was largely tensile.

The liquefaction resistance (τ_ℓ) of each of the reconstituted samples normalized by the consolidation pressure σ'_c is summarized in Figure 2. The resistance decreases with increase in void ratio or in the number of cycles to cause liquefaction. For a given void ratio, τ_ℓ/σ'_c is not dependent on the consolidation pressures, within the range studied herein.

The τ_ℓ/σ'_c values for this silt are significantly lower than those of sandy soils. Seed and Peacock (Ref. 1) shows that τ_ℓ/σ'_c decreases with the mean grain size D_{50} for sand with a relative density (D_r) of 50% (Figure 3). Their work stopped at $D_{50} \approx .07$ mm. The results of the present study plotted on the same figure show that the liquefaction resistance of this silt at a D_r of 50% would be substantially lower than the extended curve for the sandy soils.

Figure 4 compares the liquefaction resistance of reconstituted and undisturbed samples. Liquefaction is unambiguously defined for the reconstituted samples at a pore pressure equal to σ'_c. However, for the undisturbed samples, no sample collapse took place after the pore pressure reached σ'_c. The resistances corresponding to double amplitude axial strains of 3% and 5% are shown in Figure 4. In general, the different liquefaction resistances of the undisturbed samples are higher than that of the reconstituted samples.

The relative magnitudes of liquefaction resistance at different load cycles are often of interest in assessing the liquefaction potential of a deposit during an earthquake, because there is a statistical relationship linking the number of load cycles to the earthquake magnitude (M). This relationship enables the extrapolation of field experience from one earthquake magnitude to another. Seed et al. (Ref. 2) used this approach and suggested a series of values based on laboratory tests mostly on sand. A similar series of values can be obtained for the silt from the present study and a comparison is made in Table I. The comparison shows that for this silt at different void ratios, the relative values of liquefaction resistance at different earthquake magnitudes are practically equal to those suggested by Seed et al. (Ref. 2).

TABLE I. Relative liquefaction resistance at different earthquake magnitudes on the Richter Scale

Magnitude of earthquake on Richter Scale	Equivalent load cycles	Relative liquefaction resistance				
		Suggested by Seed et al	Present Study Void ratio			
			0.55	0.60	0.62	0.65
8.5	26	.89	0.85	0.87	0.87	0.85
7.5	15	1.0	1.0	1.0	1.0	1.0
6.75	10	1.13	1.11	1.11	1.11	1.11
6.0	5-6	1.32	1.30	1.28	1.30	1.28

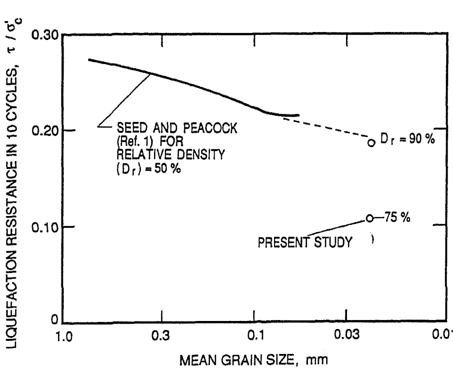

FIGURE 3

LIQUEFACTION RESISTANCE IN 10 CYCLES vs MEAN GRAIN SIZE

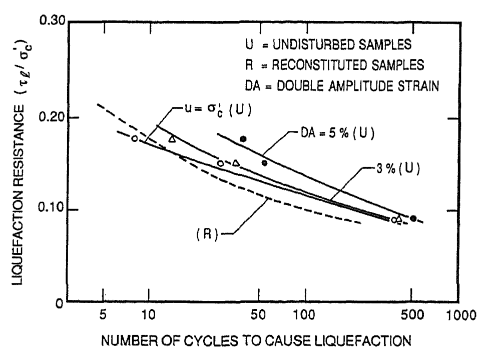

FIGURE 4

COMPARISON OF LIQUEFACTION RESITANCE BETWEEN UNDISTURBED AND RECONSTITUTED SAMPLES

Piezocone Tests

The corrected tip resistance (q_c), pore pressure (u) and sleeve friction ratio (f/q_c) for a typical piezocone sounding are shown in Figure 5. The results indicate that for the tested depth, the subsoil is mainly silt with sand layers.

Liquefaction resistance can be obtained from the piezocone data using the method by Seed et al. (Ref. 2). This method, applicable to horizontal, saturated ground, is based on the study of many earthquake records with magnitude on the Richter scale (M) of about 7½. Empirical relationships are established between τ_ℓ/σ_c' and the modified standard penetration resistance (N_1). Two such relationships were used in this study, one for clean sand and one for silty sand with the average grain size, D_{50}, less than 0.15 mm. The N_1 values in these relationships can be obtained from the piezocone test using the following equations:

$$q_{c1} = C_N q_c$$

and

$$N_1 = q_{c1}/K$$

where C_N is a coefficient to account for the effective overburden pressure (Ref. 2) and K is a conversion factor. Based on the study of Law et al. (Ref. 3), K for this site is equal to 4.25. This value is within the range recommended by Seed et al. (Ref. 2) but higher than that by Robertson et al. (Ref. 4).

A similar relationship by Iwasaki et al. (Ref. 5) was also used in this study. This relationship was established mostly from laboratory tests on silty sand with 50% fines.

The deduced liquefaction resistance from the piezocone data for M=7.5 are shown in Figure 6. There is a significant difference in the different methods used. The liquefaction resistance is highest from the method of Seed et al. (Ref. 2) for silty sand. That of Iwasaki et al. (Ref. 5) is in good agreement with that from Seed et al. for sand. The liquefaction resistance from the laboratory tests on reconstituted samples is also plotted in the same figure. Based on the method of Seed et al., the liquefaction resistances for sand and for silty sand are 66% and 100% higher than that from the cyclic triaxial tests.

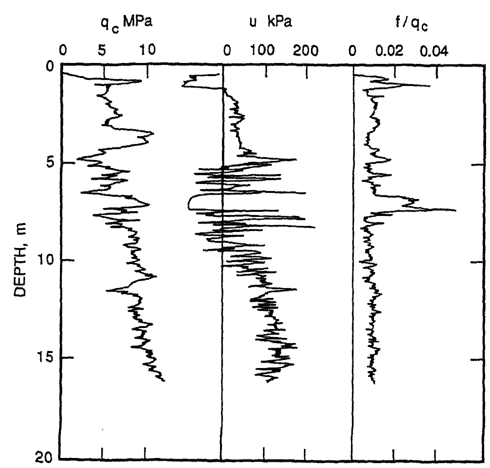

FIGURE 5

TYPICAL PIEZOCONE PROFILES

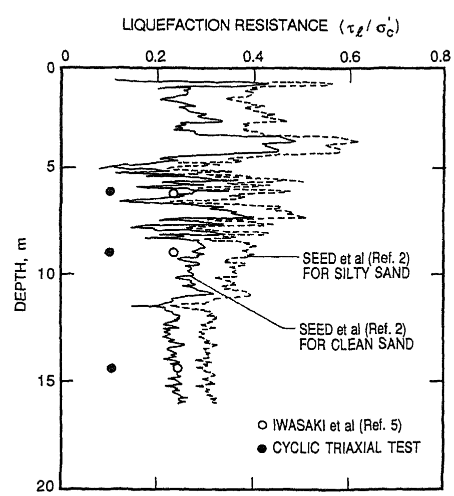

FIGURE 6

LIQUEFACTION RESISTANCE DEDUCED FROM VARIOUS METHODS FOR M = 7 1/2

DISCUSSION

Two different opinions exist regarding the effects of grain size on the liquefaction resistance, τ_ℓ, of granular soils. The first states that the smaller the grain size, the lower is τ_ℓ (e.g., Refs. 1, 6 and the present study). In this case, a silt is more liquefiable than sand. On the other hand, there is a large amount of data (e.g., Refs. 2, 5 and 7) showing that the liquefaction resistance is higher for smaller grain size, as indicated by a larger fines content.

These conflicting opinions can be resolved by considering the nature of fines in the soils. The fines in the soil tests supporting the first opinion are invariably nonplastic and provide no cohesive strength to the soil. The second opinion is based on tests of soils with fines which are generally plastic. Such fines provide a certain cohesive strength which is significant in maintaining the integrity of soil at low effective stress as a result of the high pore pressure generated by the cyclic load. This view is supported by the Chinese engineers (Ref. 8). They observed that liquefied silty soils generally have a plasticity index less than 10.

The interpretation of the piezocone data by Seed et al. (Ref. 2) for silty soil is based on materials containing plastic clay minerals. When applied to silt with insignificant clay mineral content, the interpreted τ_ℓ will be too high and unsafe. Even if the interpretation for sand is used to produce a lower τ_ℓ, it is still higher than that of the nonplastic silt as shown in this study. Therefore, the application of piezocone data for measuring liquefaction resistance should be done with caution and the plasticity index of the soil should be determined to provide additional information to assess the reliability of such an application.

Cohesion also plays an important role in contributing to the different behaviour observed between undisturbed and reconstituted samples. The soil in the field often acquires a certain apparent cohesion due to delayed consolidation over its geological history as explained by Bjerrum (Ref. 9). Recent study on a silty sand carried out at the authors' laboratory, has indicated the existence of such an apparent cohesion at low effective stress. This cohesion increases the resistance to deformation under an external load. Hence, the soil will behave like a dense sand. Sampling of the soil will introduce disturbance that may reduce the apparent cohesion. The reconstituted samples, particularly of the nonplastic soil, are an extreme case in which the cohesion is completely eliminated. Therefore, the resulting behaviour will resemble that of loose sand and the reconstituted sample will have a lower liquefaction resistance than the undisturbed sample.

The large difference in liquefaction resistance, τ_ℓ, noted in this study can now be properly understood. The interpretation by Seed et al. (Ref. 2) is based on piezocone tests in silty sand with plastic fines. This interpretation overestimates τ_ℓ for the nonplastic silt. On the other hand, tests on reconstituted silt samples underestimate τ_ℓ because of the complete elimination of cohesion. Consequently, the resistances from these two methods are very different. The true value probably lies somewhere in between. The undisturbed samples used in this study have experienced some mechanical disturbance during sample extrusion. Hence, the liquefaction resistance is also lower than the true value.

From the above consideration, it is clear that no matter how useful the tests on reconstituted samples are for studying the effects of various parameters, they are not suitable for estimating the true cyclic strength of a natural deposit. Even if undisturbed samples are used, great care should be exercised in the sampling and trimming techniques in order to produce a high quality specimen for testing.

SUMMARY AND CONCLUSIONS

Cyclic triaxial tests and piezocone penetrometer tests were conducted on a nonplastic silt in order to study its liquefaction resistance. The cyclic triaxial tests indicate the following:

(1) The liquefaction resistance of this silt is lower than that of sand.
(2) The relative liquefaction resistance for different earthquake magnitudes (M) normalized by the resistance corresponding to M=7½ is practically equal to that for sand.
(3) The undisturbed sample behaves like a dense sand while the reconstituted sample behaves like a loose sand.

The piezocone penetrometer tests show that the liquefaction resistances based on the interpretation of Seed at al. (Ref. 2) for sand and for silty sand are, respectively, 66% and 100% higher than that obtained from the triaxial tests.

The difference in behaviour between undisturbed and reconstituted samples and the discrepancy in liquefaction resistance between laboratory and field tests are attributed to an apparent cohesion that may develop over the geological history of the deposit or may be caused by the presences of plastic fines. Therefore, in dealing with silt, special care should be taken to assess the nature of the fines and to obtain high quality undisturbed samples.

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