14 Mar 1991, 10:30 am - 12:30 pm

# The Characteristics of Residual Strength of Silt Under Liquefaction Conditions

H.-C. Fei
*Tongji University, Shanghai, China*

F. Lu
*Nejin Architecture Design Institute, Nejin, China*

Proceedings: Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, March 11-15, 1991, St. Louis, Missouri, Paper No. 3.49

# The Characteristics of Residual Strength of Silt Under Liquefaction Conditions

**H.-C. Fei**
Associate Professor, Department of Civil Engineering, Tongji University, Shanghai, 200092, China

**F. Lu**
Engineer, Nejin Architecture Design Institute, Nejin, China

SYNOPSIS Silt soil is defined as a soil whose fine particles ($D_{50}$<0.005mm) content is from 3% to 15%. The Tangshan earthquake of 1976 had a magnitude of 7.8 and caused the liquefaction of silt soil in large areas in Tianjin City. The seismic intensity at Tianjin was 8° in downtown. Currently the same criterion for initial liquefaction is applied to silt and sand, e.g., the development of pore pressure, u, equal to the effective confining pressure $\sigma_o'$. However, in silt residual strength still exists because of cohesion due to the finest of the particles even when $u=\sigma_o'$ due to shaking. The authors employed a superimposed ring shear device to study the characteristics of residual shear strength of silts with different fine particle contents and with various pore pressure ratios, $u/\sigma_v'$ under both dynamic and static loads.

## INTRODUCTION

It has been demonstrated by earthquakes in China in recent years, such as the Tangshan earthquake in 1976, that not only the liquefaction of fine sand is very easy to develop, but also some types of silts will liquefy under earthquake loads. Besides the geological and geographical conditions, ground water table, seismic magnitude and duration; the main factor that influences the liquefaction potential of soil is grain size distribution. In China silt soil is generally defined as a soil whose fine particle ($D_{50}$<0.005mm) content, Pc, is from 3% to 15% and for which the plastic index is less than 10%. For silt the fine particle content strongly affects the liquefaction potential (Shi, 1982, 1984; Zhou, 1982). Based upon the results of laboratory tests and the records of the field investigations in seismic areas, the liquefaction resistance of silt soil varies with different particle size content. Table 1 and Fig. 1 show the maximum fine particle content of liquefied silt in different seismic intensity areas in the Tangshan Earthquake.

TABLE 1

Fines Content of Silts That Liquefy

| Seismic Intensity (I) | Fine Particle Content (Pc %) |
|---|---|
| 7 | 10 |
| 8 | 13 |
| 9 | 16 |
| 10 | 19 |

It can be seen clearly in Table 1 and Fig. 1 that the liquefaction resistance of silt soil increase with an increase of fine particle content. In laboratory tests it is normal to

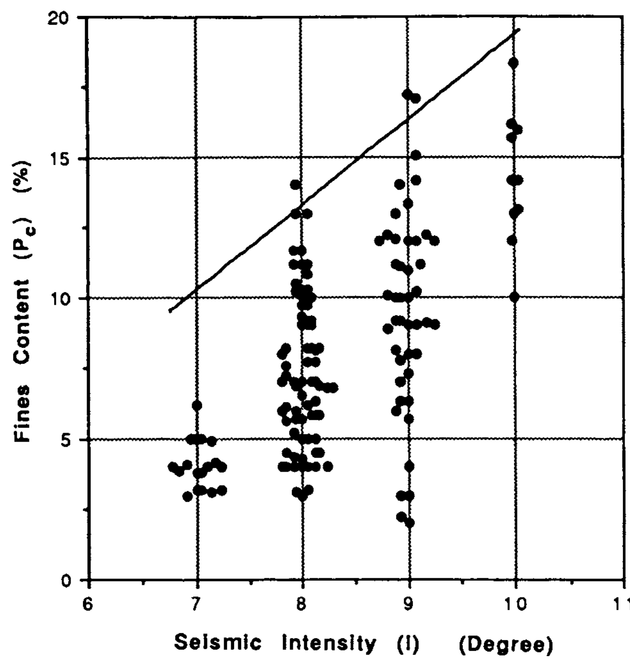



Fig. 1 Relationship between Fines Content and Seismic Intensity in Tangshan Earthquake

follow the same criterion for initial liquefaction as for sands, i.e. the silt is in initial liquefaction state when the pore pressure in the silt is equal to the effective confining pressure due to shaking. But, for silt, the equation for strength has both friction and cohesion components and can be written as;

$$\tau = (\sigma - u) \tan \phi + C \qquad (1)$$

where $\tau$ = shear strength of soil
u = pore pressure in water phase
C = cohesion intercept
$\sigma$ = total stress
$\phi$ = angle of internal friction.

It is obvious that silt is different from sand. The shear strength of silt is not equal to zero when the pore pressure in the silt reaches the confining pressure because the size of the silt particle is smaller than sand and silt has cohesive residual strength. In this paper the authors investigated the characteristics of the residual cohesion in silts and its relation to fine particle content under liquefaction conditions.

## TESTING DEVICE AND METHOD

The superimposed ring dynamic/static shearing device, Fig. 2 manufactured in the Tongji University shops was employed to measure the residual strength of silt. A soil sample 6 cm in diameter and 2 cm thick is tested. The specimen can be either undisturbed or remolded. After being saturated under vacuum, the samples were consolidated under a selected confining pressure. Then, the sample was put in the superimposed ring shear device surrounded by a membrane and shaken in the horizontal direction under undrained conditions until the pore pressure reached the confining pressure. After that, a static horizontal shear force was applied on the undrained sample along the middle plane of the sample. The curves in Fig.3 show the general relation between shear stress, pore pressure and shear strain.

## RESULTS AND ANALYSIS

The curves in Fig.3 show separately, for two different silts with different Pc, the relation between the residual shear strength, pore pressure and static shear strain under undrained conditions. Before the test, it was assumed that the state of initial liquefaction begins when the developing pore pressure in the sample caused by shaking reaches the confining pressure. In these tests a static simple shear force was applied to the sample when the pore pressure ratio reached 1. With increase of the static shear strain, the pore pressure in the sample decreased and shear stress of the sample increased steadily. This means that the shear dilation phenomenon occurs in the sample. Finally, when the pore pressure stopped decreasing, the shear stress reached its maximum value, after which the shear stress did not change with increasing shear strain, and the soil sample was in a plastic state. The maximum shear stress can be taken as the ultimate residual strength, $\tau_m$.

It can be observed that the ultimate residual strength is controlled by pore pressure in the soil, and that the variation of pore pressure is influenced by the fine particle content of the soil. If the fine particle content is over 14%, only slight shear dilatancy occurs. If the pore pressure does not dissipate, the ultimate residual strength cannot develop, Fig. 3a. Conversely, if the content of fine particles is small, significant dilatancy occurs during simple shear and the pore pressure dissipates quickly and the ultimate residual strength is high, Fig. 3b. In Table 2 are listed the

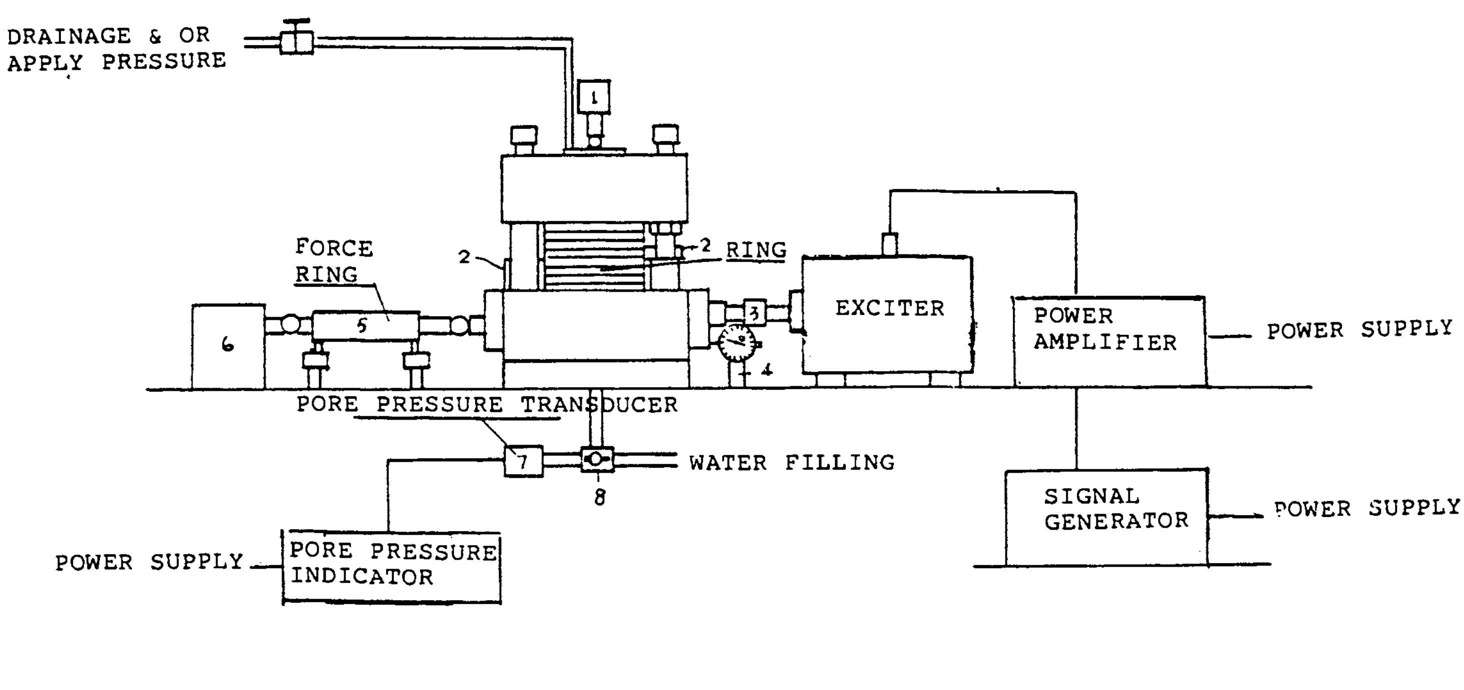
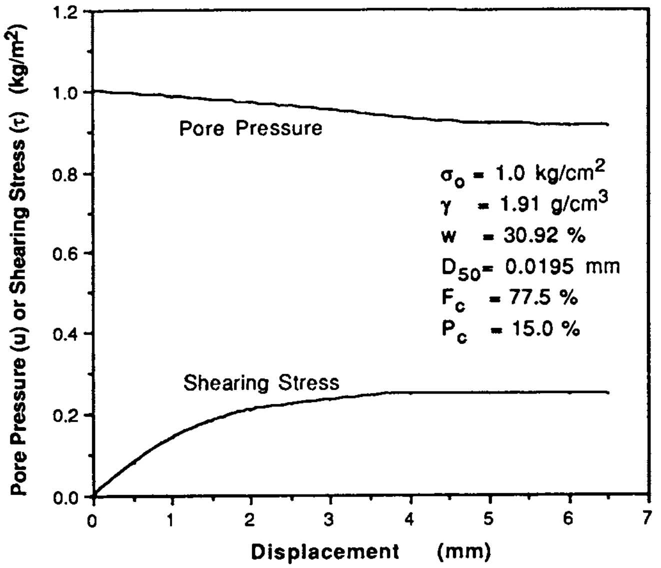
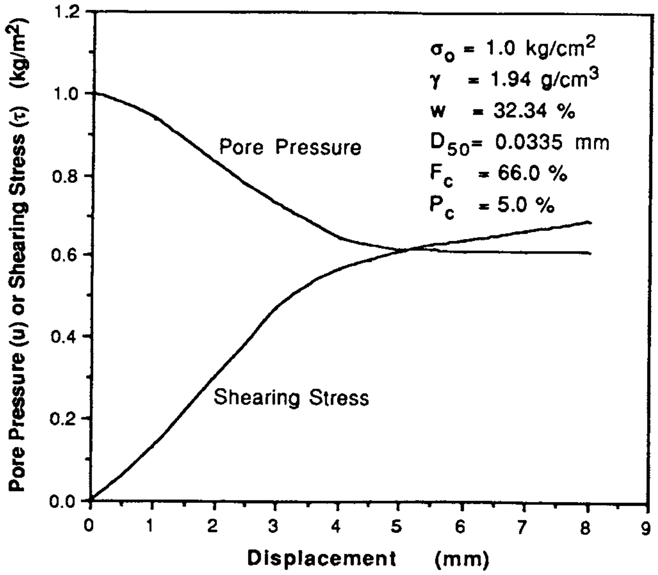



Fig. 2. Sketch of the dynamic-static shearing device.




(a) Sample 2-3




(b) Sample 6-2

Fig.3 Relationship between Pore Pressure or Shearing Stress and Displacement

pore pressure values of various silts with different fine particle contents and mean particle diameters, $D_{50}$, at three strain levels.

To cancel the effect of the dissipation of pore pressure by shear dilatancy on residual strength during simple shear under pore pressure ratio = 1, a tube was connected to the ring box of the device to apply a static pore pressure. This way it was possible to maintain a certain water head in the soil sample during shear, thus decreasing or avoiding the loss of water head due to dilatancy.

Samples L-1, L-2, L-3 with the same particle distribution and physical property index

TABLE 2

Pore Pressures at Three Strain Levels for Various Silts

| Sample No. | $D_{50}$ (mm) | Pc (%) | Pore Pressure, u (kg/cm$^2$) S1* | S2 | S3 | min |
|---|---|---|---|---|---|---|
| 2-3 | 0.0195 | 15.0 | 0.98 | 0.98 | 0.97 | 0.95 |
| 4-3 | 0.022 | 14.0 | 0.91 | 0.89 | 0.86 | 0.82 |
| 1-1 | 0.023 | 12.4 | 0.81 | 0.81 | 0.77 | 0.65 |
| 1R-1 | 0.034 | 7.0 | 0.83 | 0.79 | 0.71 | 0.58 |
| 6-5 | 0.0245 | 6.5 | 0.93 | 0.91 | 0.87 | 0.80 |
| 5R-2 | 0.040 | 6.0 | 0.85 | 0.80 | 0.72 | 0.51 |
| 4R-1 | 0.070 | 5.5 | 0.83 | 0.78 | 0.68 | 0.51 |
| 6-2 | 0.0335 | 5.0 | 0.79 | 0.76 | 0.68 | 0.65 |
| 6R-2 | 0.046 | 3.7 | 0.83 | 0.79 | 0.71 | 0.63 |

* S1, S2, S3 shear displacement, equal to 2.1mm, 2.4mm, 3.0mm respectively, min = minimum pore pressure.

were tested with water heads of 0, 1 and 1.12 kg/cm$^2$. The test results are shown in Fig. 4 where it can be seen that the loss of pore pressure caused by dilatancy is reduced by the additional water head and the increase of the residual strength is limited. The pore pressure ratio in sample L-3 was decreased to 0.975. The maximum residual strength $\tau_m$ of sample L-3 was 0.21 kg/cm$^2$. This corresponds to $u/\sigma'_v$ = 0.975 and is close to the residual strength of silt under pore pressure ratio of 1. The relation between the residual strength and the pore pressure ratio is shown in Fig. 5. It can be seen in Fig. 5 that this is a linear relation whenever the additional water head was applied to the sample to maintain the pore pressure.

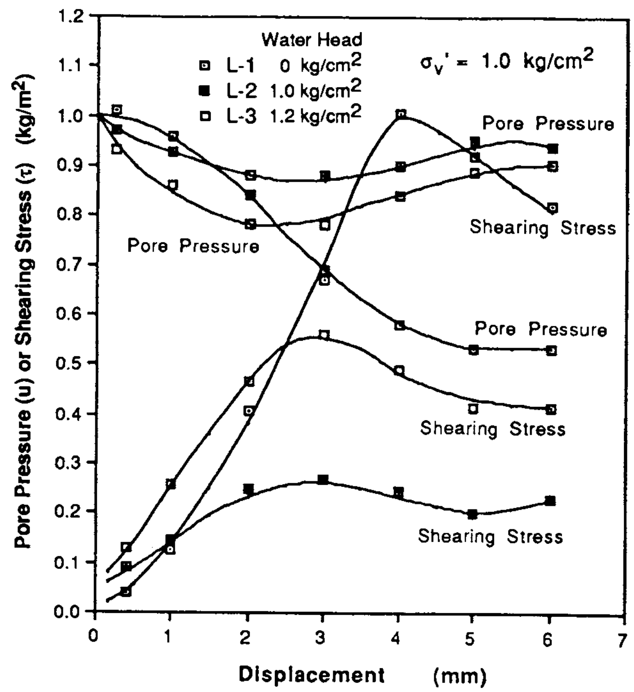



Fig.4 Relationship between Pore Pressure or Shearing Stress and Displacement

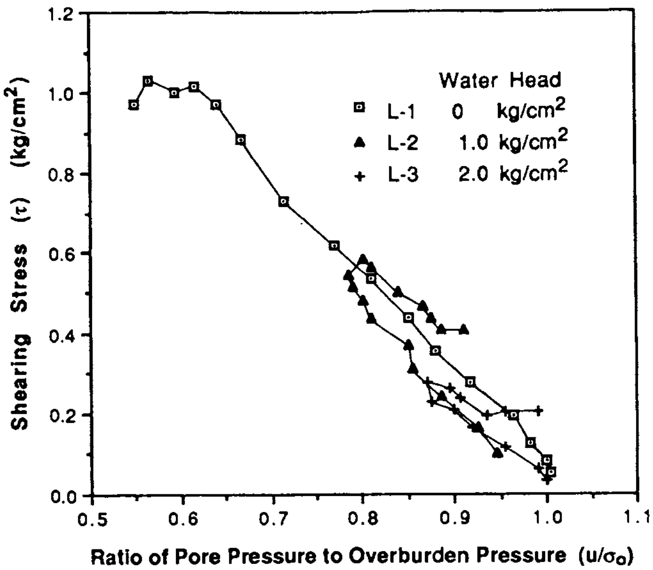



Fig.5 Relationship between Shearing Stress and Ratio of Pore Pressure to Overburden Pressure

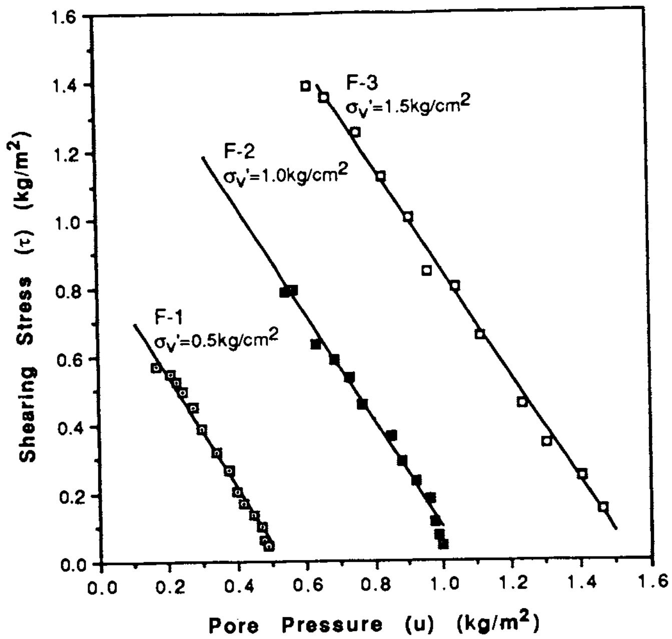



Fig.6 Relationship between Shearing Stress and Pore Pressure

Figure 6 shows a family of test curves presenting the effect of confining pressure on the relation between shearing stress and pore pressure. Different confining pressure, 0.5, 1.0 and 1.5 kg/cm$^2$ were applied to these samples which had the same physical properties. The three curves show a linear relation and have the same slope. This means that there is no effect of the confining pressure on the relation, so the linear relation can be written as:

$$\tau = \tau_o + B\ (1 - u/\sigma'_v) \qquad (2)$$

or

$$\tau = \tau_o + A\ (u_o - u) \qquad (3)$$

where

$\tau$ = the residual strength at a given u
$\tau_o$ = initial residual strength at $u/\sigma'_v=1$
$u$ = pore pressure in soil
$u_o$ = critical pore pressure, equal to
B, A = slope of the curve, $B = A/\sigma'_v$.

Slope B and A representing the variation of the residual strength of the soil with the pore pressure is a characteristic index of the variation of the residual strength. The relation between slope coefficient A and fine particle content, Pc, is shown in Fig. 7. Within a fine particle content range of 3% to 15%, the relation between A & Pc can be expressed as:

$$A = 1.31 \exp (1.61/Pc) \qquad (4)$$

where exp is the base of the natural logarithm. Also, the relation between the initial residual strength $\tau_o$ and Pc within the range of Pc 3% to 12% can be written as: (see Fig. 8)

$$\tau_o = 22.4 \exp (-4.42/Pc) \qquad (5)$$

It is clear that A will increase with the decrease of Pc and $\tau_o$ will increase with the increase of Pc.

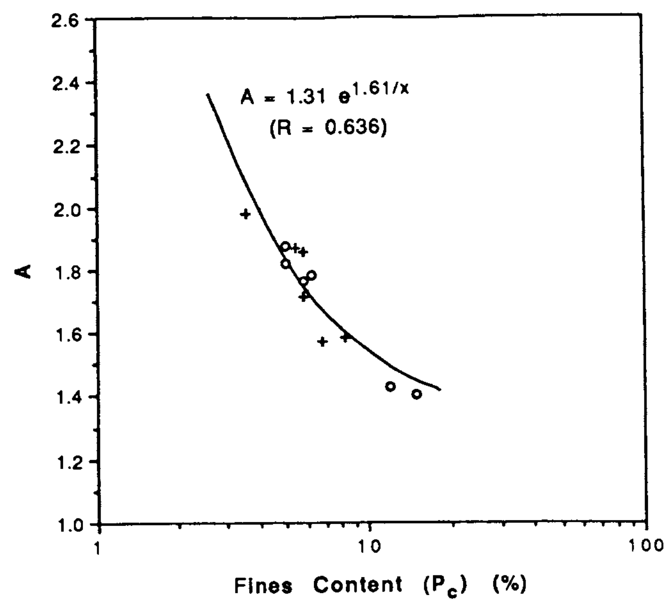



Fig. 7 Relationship between A and Fines Content

A study of the areas that liquefied in the Tangshan earthquake in 1976 showed that only a very few of the silts with fine particle contents over 12.5% liquefied in that intensity 8 event. This means that silt with a high percentage of fine particles has considerable resistance to liquefaction due to residual strength preventing pore pressure buildup by shaking. More energy is required to develop much higher pore pressure to cause the liquefaction of silt soil.

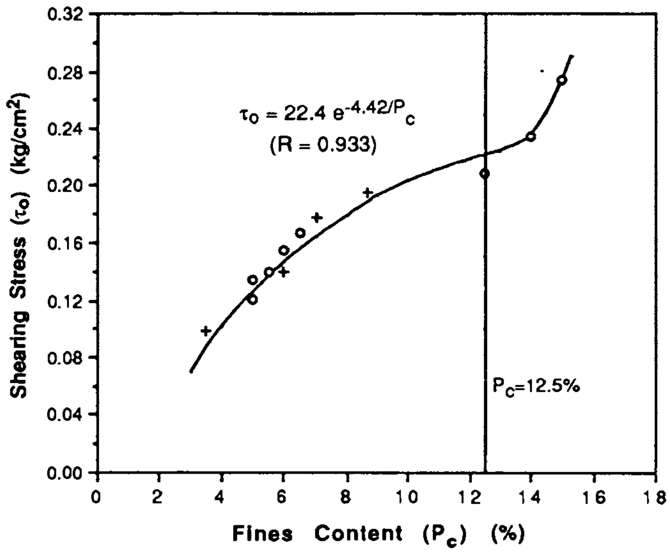



Fig.8 Relationship between Shearing Stress and Fines Content

## CONCLUSIONS

1) Residual strength exists in silt soil under pore pressure ratios = 1 and residual strength increased with an increase in fine particle content.

2) It is unreasonable to use the criterion for the initial liquefaction of sand ($u/\sigma'_v=1$) as a criterion for silt.

3) It may be convenient to take the dynamic shear strain as the criterion of initial liquefaction for silt soil.

4) Empirical equations (4) & (5) represent the effect of fine particle content of silt on residual strength. These equations can be used to estimate liquefaction resistance.

## REFERENCES


Zhao-jie Shi (1982), "The Characteristics of Liquefaction of Silt and the Prediction in the Field," Hydraulic Geology & Engineering Geology, No. 3.

Zhao-jie Shi (1984), "The Prediction of Liquefaction Potential of Saturated Silt Soil Foundation," Earthquake Engineering & Engineering Vibration, Vol. 4, No. 3.

Jing-xing Zhou, et al (1982), "The Pore Pressure & Liquefaction Characteristics of Silt Soil," Report of Qinghua University.