27 Apr 1981, 10:30 am - 1:00 pm

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H. Y. Fang
Lehigh University, Bethlehem, PA

R. C. Chaney
Lehigh University, Bethlehem, PA

N. S. Pandit
Lehigh University, Bethlehem, PA

Proceedings: First International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, April 26 - May 3, 1981, St. Louis, Missouri

Dynamic Shear Modulus of Soft Silt

H. Y. Fang, Professor and Director
Geotechnical Engineering Div., Lehigh University, Bethlehem, PA

R. C. Chaney, Associate Professor
N. S. Pandit, Research Assistant
Lehigh University, Bethlehem, PA

SYNOPSIS This paper presents the geotechnical properties of soft silt obtained from the Greater Shanghai Region of the People's Republic of China. Fundamental correlations of shear modulus, damping ratio, shear stress, shear strain with varying consolidation pressures are determined in the laboratory by cyclic simple shear tests. A comparison is made between laboratory test results, in situ cross-hole test results and the building code data proposed by the Shanghai Municipal Bureau. Finally, a comparison of the laboratory data on Shanghai silt with other published data on sands and clays is presented and discussed.

INTRODUCTION

The shear modulus of soil is one of two fundamental soil parameters required for the analysis of the response of soil structures and soil-structure interaction under dynamic loading. A review of the literature indicates that most available information deals with the commonly encountered soils composed of sands and clays. Very little factual data exists relating to the dynamic properties of silt.

Silt covers large areas around the world especially along the coastal regions. Due to recent interest in offshore construction, this type of soil has been given considerable attention by many geotechnical engineers. From the particle size point of view, silt ranges between sand and clay. However, silt has its own special characteristics with respect to compressibility, shear strength and other geotechnical behavior. This paper presents experimental data obtained from the Greater Shanghai Region of the People's Republic of China. The data was generated during the course of recent construction in the region (Fang, 1980; Tong, 1979; Wang, et al, 1978).

The material covered in this paper includes the following: (1) geotechnical properties of Shanghai silt, (2) laboratory cyclic simple shear results, (3) in situ cross-hole tests, and (4) comparisons of laboratory test results with published empirical relationships such as those developed on sands and clays by Hardin-Drnevich (1972), Seed-Idriss (1970), Shibata-Soelarno (1975), and those using the Ramberg-Osgood curve fit (1943). Finally, experimental test results from both laboratory and in situ test programs are compared with the corresponding data on dynamic shear modulus proposed by the Shanghai Foundation Code (1975).

GEOTECHNICAL PROPERTIES OF SHANGHAI SILT

Wet and soft alluvial deposits cover large areas of the populated lower Yangtze valley as shown in Fig. 1. North of Shanghai along the coastal areas are clay deposits containing appreciable

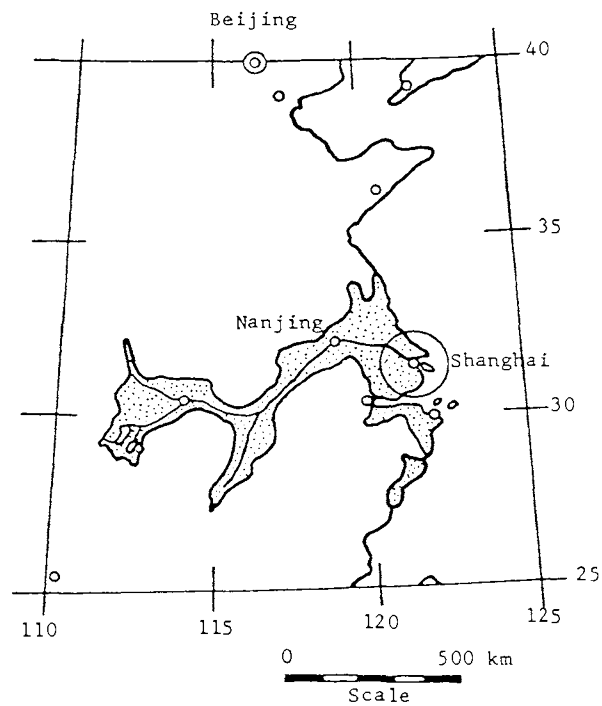

Figure 1 General Location of Soft Alluvial Deposits. Circle Indicates on the Map the Greater Shanghai Region.

amounts of soluble salts. There are three major soil types in the vicinity of the Greater Shanghai Region (Tong, et al. 1979; Wei and Fu, 1979) A typical soil profile is shown in Fig. 2. The first 30 meters from the ground surface is called the shallow strata of a foundation layer. This layer consists of a 3 meter surface layer of drying soil of dark brown color and is relatively hard. It has been used as a shallow foundation supporting strata. The second layer is about 20 meters deep, gray colored and soft containing organic matter, shells and some very fine sand at a depth below 18 meters. The silt content based on the sieve analysis varies from 35% to 88% in this layer. This soft silt layer is distributed over large areas of the Greater Shanghai Region and creates great difficulties for geotechnical engineers. In the following section, the discussions are focused on the soft silt layer, however, some comparisons are made to the other two layers.

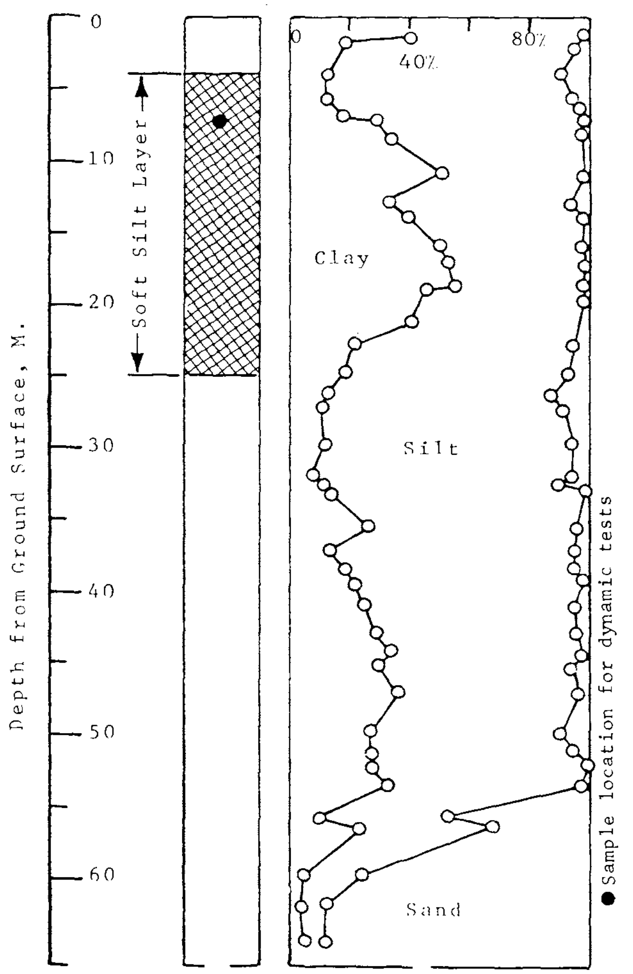

Figure 2 Grain Size Distribution of Shanghai Soils

The major soil parameters of Shanghai soil are summarized in Fig. 3 from ground surface to approximately 60 meters in depth. These parameters include standard penetration resistance, N, initial void ratio, e_o, initial water content, w_o, unconfined compressive strength, q_u, laboratory triaxial shear tests for both drained and undrained conditions have been performed. In situ vane shear and static cone resistance tests are also made. The pore pressure parameter A at failure varied from 0.70 to 0.86. The stress history is expressed by the overconsolidation ratio (OCR) which varies with depth, z. A simple relationship was established as follows (Wei and Hu, 1979):

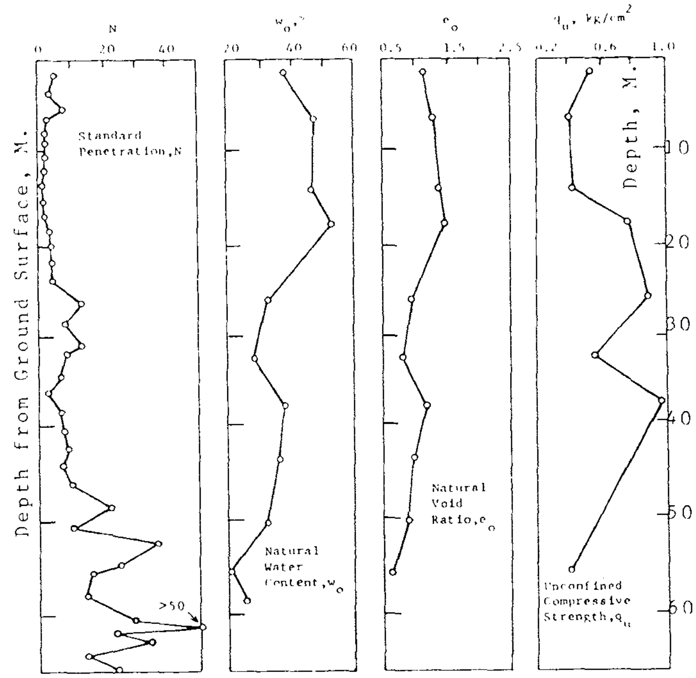

Figure 3 Some Typical Geotechnical Properties of Shanghai Soils

For depths from 0 to 4 meters:

$$OCR = 12.64 - 3.44\ z \qquad (1)$$

For depths from 4 to 25 meters:

$$OCR = 0.0046\ (z - 3) + 1.03 \qquad (2)$$

It can been seen from above relationships, the overconsolidation ratio for the first 4 meters reaches as high as 12.0. For the depths between 4 to 25 meters, which contain large percentages of soft silt, the average OCR value is 1.08. The corresponding average value for the dark green stiff clay between 25 to 32 meters is 2.15. In this paper emphasis is placed on the middle layer which contains large amounts of silt where the OCR is low and the standard penetration resistance, N, varies from 2 to 8. The void ratio varies from 0.88 to 1.50. The degree of saturation varies from 91% to 100%. The ground water table is very shallow, varying from 0.3 to 1.5 meters from the ground surface. The annual average values are approximately from 0.5 to 0.7 meters.

DYNAMIC TEST PROGRAM

Laboratory stress controlled cyclic simple shear apparatus using a wire bound membrane and in situ cross-hole tests were used for evaluation of the dynamic properties of Shanghai silt. The laboratory tests were performed by the Eastern China Hydraulic Institute on three undisturbed samples obtained by thin wall tube sampler (Wang, et al. 1979). The samples were taken from depths between 6 to 10 meters which are classified as the soft silt zone as discussed previously. The physical properties of the test samples were:

Natural Moisture Content, w_o = 34%

Unit Weight	$= 1.86\ g/cm^3$
Liquid Limit, L.L.	= 34
Plasticity Index, P.I.	= 10
Degree of Saturation, S	= 97.0%
Initial Void Ratio, e_o	= 0.96

Samples were prepared for testing by extruding from the thin wall tube sampler, trimmed to the desired cylindrical dimensions and placed in the cyclic simple shear apparatus. Trimmed sample dimensions were (1) diameter (D) = 7 cm, (2) height (H) = 2 cm. These values correspond to a H/D ratio of 0.29. Samples were consolidated for a period of 12 hours under pressures ranging from 0.47 to 0.80 kg/cm^2 to simulate the overburden pressure in the Shanghai region prior to testing.

Dynamic property tests using a staged procedure were performed on undrained samples. The staged procedure consisted of applying a known low cyclic load and observing the resultant shearing strain level achieved after three cycles of load. The process was then performed again on the same sample by increasing the cyclic load and observing the increased shearing strain level. This process was performed for six separate stages on each sample. The resultant shearing strain levels ranged from approximately 1.8×10^{-2}% to 2.2×10^{-1}%. The cyclic load was applied to the sample at a frequency of 2 Hz. A summary of test results is presented in Table 1 and plotted graphically in Fig. 4 as shear stress (τ), shear modulus (G) and damping ratio versus shearing strain (γ).

TABLE I. Summary of G/G_{max} and γ/γ_r Ratios with Various Shear Modulus (G), Shearing Strain (γ) and Effective Consolidation Pressure ($\bar{\sigma}_v$) of Shanghai Soft Silt.

Sample No	$\bar{\sigma}_v$ kg/cm^2	G kg/cm^2	G/G_{max}	γ cm	γ/γ_r
	0.47	95.0	0.940	0.00022	0.100
		85.0	0.842	0.00049	0.245
1		75.00	0.743	0.00096	0.409
		67.5	0.668	0.00116	0.527
		65.0	0.643	0.00150	0.682
		50.0	0.495	0.00216	0.980
		G_{max} = 101.0 kg/cm^2; γ_r =0.0022cm			
	0.67	100.0	0.880	0.00022	0.100
		100.0	0.880	0.00049	0.245
2		85.0	0.748	0.00096	0.436
		70.0	0.616	0.00136	0.618
		65.0	0.572	0.00162	0.736
		50.0	0.440	0.00205	0.932
		G_{max} = 113.6 kg/cm^2; γ_r =0.0022cm			
	0.80	130.0	0.975	0.00018	0.090
		115.0	0.860	0.00040	0.200
3		105.0	0.790	0.00066	0.330
		95.0	0.710	0.00096	0.480
		90.0	0.675	0.00116	0.580
		85.0	0.637	0.00134	0.670
		G_{max} = 133.3 kg/cm^2; γ_r =0.0020cm			

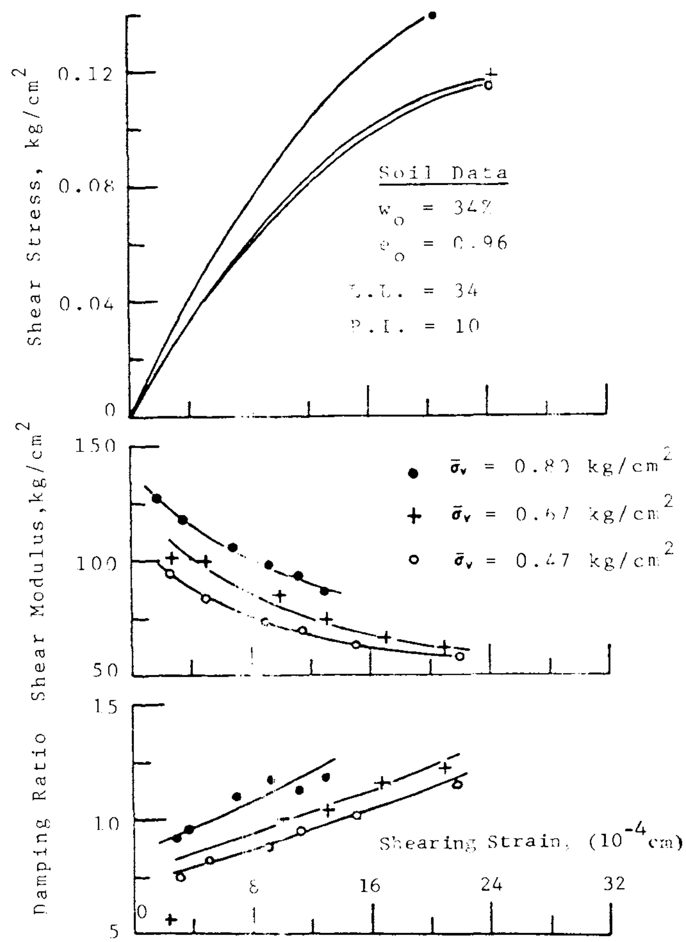

Figure 4 Correlations of Shear Stress, Shear Modulus, Damping Ratio and Shearing Strain of Shanghai Soft Silt.

ANALYSIS OF TEST RESULTS

For normally consolidated soils, the use of the "reference strain" approach to normalize stress-strain data provides a curve which is independent of the effective stress path and sample disturbance (Drnevich, 1979). Hence, the normalized stress-strain curve produced by this technique should apply to in situ conditions.

The normalization of the test data presented in Fig. 4 requires values of τ_{max} and G_{max} at low shearing strain levels ($\leq 10^{-4}$). The maximum shear modulus (G_{max}) may be computed by two procedures. The first procedure was presented by Hardin and Drnevich (1972) where the shear modulus, G, was shown to be equal to the following expression:

$$G = \frac{\tau}{\gamma} = \frac{1}{a + b\gamma} \quad (3)$$

where

G = shear modulus
τ = shear stress
γ = shear strain
a, b = constants

It was also shown that the ratio of shear modulus (G) to its maximum value (G_{max}) evaluated at low shearing strains ($\gamma \leq 10^{-4}$%) could be given by

$$G/G_{max} = \frac{1}{1 + \gamma/\gamma_r} \quad (4)$$

where

$\gamma_r = \tau_{max}/G_{max}$ = reference strain

τ_{max} = shear stress at failure

combining Eqs. 3 and 4 and solving for constants a and b the following relations are obtained.

$$\left.\begin{aligned} a &= 1/G_{max} \\ b &= 1/\tau_{max} \end{aligned}\right\} \quad (5)$$

rearranging

$$\gamma_r = \frac{\tau_{max}}{G_{max}} = \frac{a}{b} \quad (6)$$

Constants a and b are determined by plotting γ/τ versus γ. A summary of a and b constants and the corresponding values of G_{max} and γ_r are presented in Table II. The G_{max} values obtained by this procedure compared closely against those obtained by using empirical equation proposed by Hardin and Black (1968) as follows:

$$G_{max} = \frac{1230\ (2.973 - e)^2}{1 + e}\ (OCR)^k\ (\bar{\sigma}_o)^{½}$$

where

e = void ratio = 0.96

OCR = overconsolidation ratio = 1.08

$k \cong 0$ (since plasticity index is very low, P.I. = 10)

$$\bar{\sigma}_o = \bar{\sigma}_v\left(\frac{1 + 2K_o}{3}\right)$$

K_o = coefficient of earth pressure at rest = 0.60

Therefore, the calculated G_{max} values are believed to be reasonable values. The calculated values for all three consolidation pressures are summarized in Table I. The final results are plotted in Fig. 5 together with published data summarized by Richart (1977).

A review of Fig. 5 shows that the cyclic response of Shanghai silt lies in the region between sand and clays

The G_{max} determined from laboratory developed parameters as given in Table I are compared against values of G_{max} from in situ cross-hole tests and the suggested Foundation Code values by the Shanghai Municipal Bureau (1975) in Fig. 6. A review of Fig. 6 shows the following (1) both values of shear modulus G_{max} increase with depth, (2) in situ G_{max} is greater than the laboratory G_{max}, and (3) the values suggested by the Foundation Code of the Shanghai Municipal Bureau are 40% greater than in situ results. The difference between the laboratory and in situ G_{max} values may be caused by (1) the mean principal effective stress used in the test is smaller than that in actual field condition, and (2) no allowance was made for the time effect of consolidation on sample stiffness

Sample No.	$\bar{\sigma}_v$ kg/cm^2	a	b	G_{max} (= 1/a) kg/cm^2	γ_r (= a/b) cm
1	0.47	0.0099	4.5	101.0	0.0022
2	0.67	0.0088	4.0	113.6	0.0022
3	0.80	0.0075	3.8	133.3	0.0020

TABLE II. Estimation of G_{max} and γ_r

SUMMARY AND CONCLUSIONS

1. Shanghai clays contain large percentages of soft silt varying from 35% to 88%. Varying thickness of sand seams or layers exist below the depth of 18 meters from ground surface.

2. Based on the stress history as indicated by the OCR, the first 4 meters are classified as hard layer with a dark-brown color with the OCR reaching as high as 12. The second layer is soft silt with an average OCR of about 1.08. This layer is between 4 to 25 meters below ground surface. The natural moisture content varies from 32% to 52% and the degree of saturation is between 91% to 100%.

3. The standard penetration value, N, for the soft silt layer is about 2 to 8. The undrained consolidated shear tests determined by triaxial shear tests show that cohesion varies from 0.15 to 0.38 kg/cm^2, and the friction angle varies from 10 to 28 degrees.

4. Comparison between Shanghai silt and other published results on sands and clays are shown in Fig. 5. It is expected that silt lies in the region between sand and clays. However, the dynamic behavior as observed in this test program is closer to that of sands than clays.

ACKNOWLEDGEMENTS

The work described in this paper is part of the cooperative research sponsored by the Committee on Scholarly Communication with the People's Republic of China and the U. S. National Academy of Sciences. Special thanks to the Eastern China Power Design Institute and Tongji University for their discussion of soil and geological problems with the senior author of this paper who served as visiting Senior Scholar at Tongji University in Shanghai from July to September, 1979 and June to August, 1980.

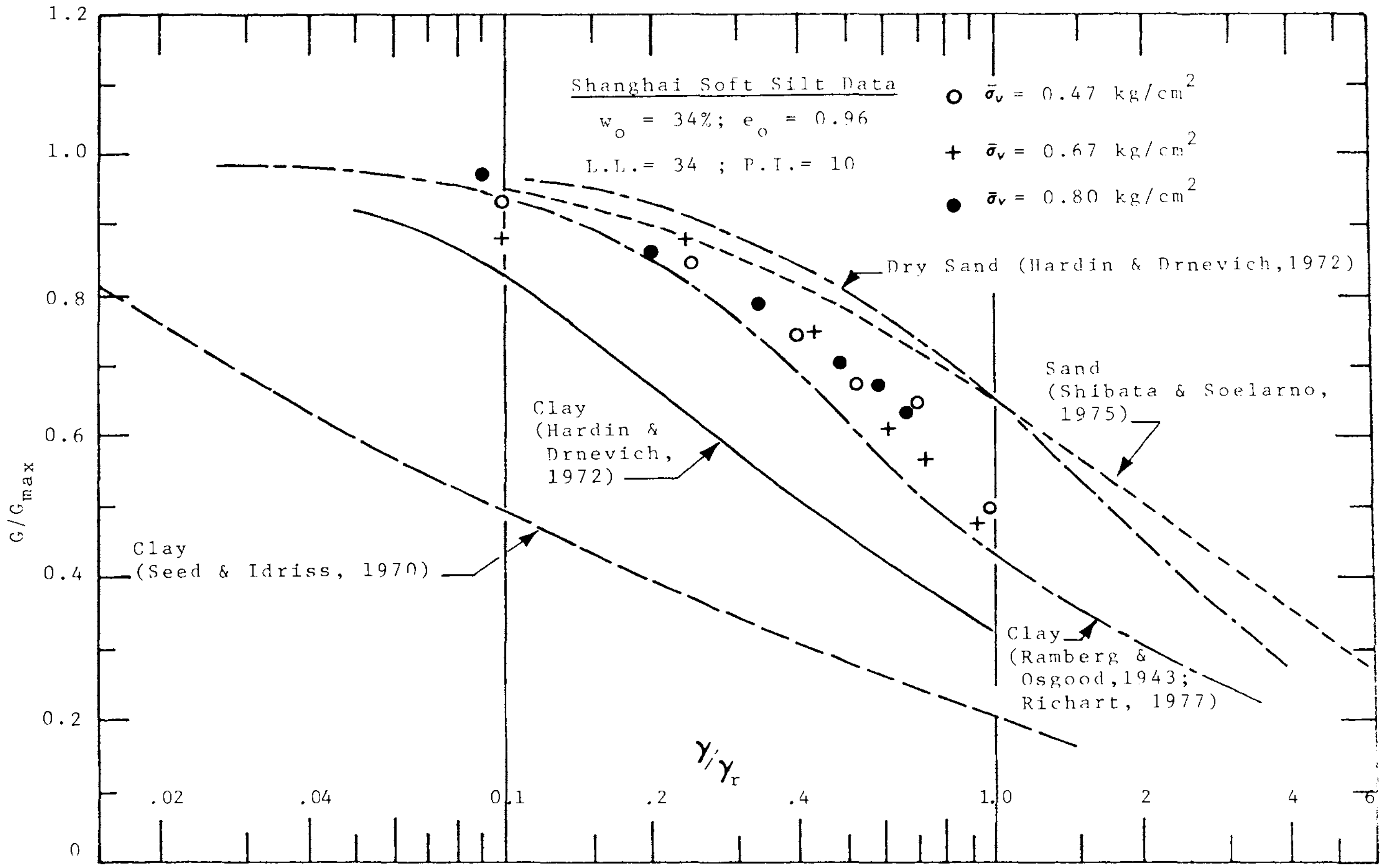

Figure 5 Comparison of G/G_{max} Versus γ/γ_r Ratios for Various Soil Types

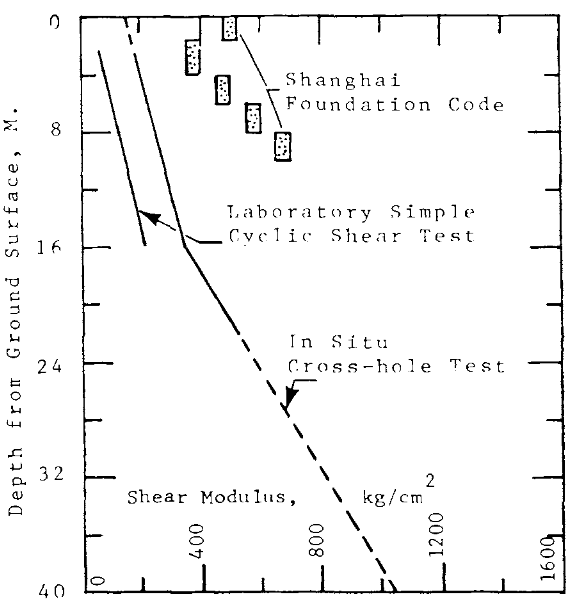

Figure 6 Comparison of Methods for Determination of Shear Modulus of Shanghai Soft Silt.

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