Stress-strain behaviour of clays

Comportement de tension-contrainte des argiles

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SYNOPSIS The dynamic stress-strain behaviour of clays can be determined accurately over a large strain range by resonant column tests. It is shown that the variation of shear modulus is strongly affected by strain amplitude. A simple approach is proposed which makes it possible to estimate the static shear modulus based on dynamic tests.

INTRODUCTION

Until recently, research efforts have mainly been focused on the development of often sophisticated analytical soil models while less attention has been given to the question how the in-put parameters can be determined. The assumption of a realistic soil model is many times the most difficult problem of geotechnical analyses. For example, only little practical information is yet available on the stress-strain behaviour of soils at low stress levels. Conventional static laboratory tests can not measure below strain amplitudes of about 0.1 per cent. At a resonant column test, however, stress-strain behaviour can readily be determined from very small strain amplitudes (0.0001 %) up to about 0.5 per cent.

The resonant column test is similar to a conventional triaxial test, as regards sample preparation (Drnevich and Hardin, 1978). A solid or hollow cylindrical sample is consolidated and then subjected to either axial or torsional vibrations. At system resonance (first mode of vibrations) the applied frequency, force and deformation are measured with high accuracy. If the strain amplitude is kept small (0.001 %), the shear modulus can be determined at several confining stresses. Strain amplitude can also be gradually increased, thus providing accurate stress-strain values over a large strain range.

The modulus determined from resonant column tests is generally referred to as the "dynamic modulus" G_{max}. However, at small strain amplitudes, e. g. 0.0001 per cent, the rate of loading is low and comparable to a conventional static test (about 0.01 per cent/sec). Isenhower and Stokoe (1981) studied in detail the effect of loading rate on shear modulus. From this comprehensive investigation it can be concluded that loading rate has little influence on shear modulus.

SHEAR MODULUS

Based on extensive resonant solumn tests, Hardin (1978) proposed a relationship from which the shear modulus at small strain G_{max}, can be estimated.

$$G_{max}= 625\cdot OCR^{k}\cdot(\sigma'\cdot Pa)^{0.5}/(0.3 + 0.7\cdot e^{2}) \qquad (1)$$

where OCR is the overconsolidation ratio, k an empirical coefficient, σ' the effective confining stress, Pa a reference pressure and e the void ratio. The shear modulus is thus related to the square of void ratio and to the square root of effective confining stress. Hardin and Drnevich (1972) proposed the concept of reference strain γ_{ref}, which is defined as the strain amplitude at which maximum shear modulus and shear strength intersect, Fig. 1. However, it was not generally recognized that reference strain is the inverse of the ratio between maximum shear modulus and shear strength (Massarsch, 1981a).

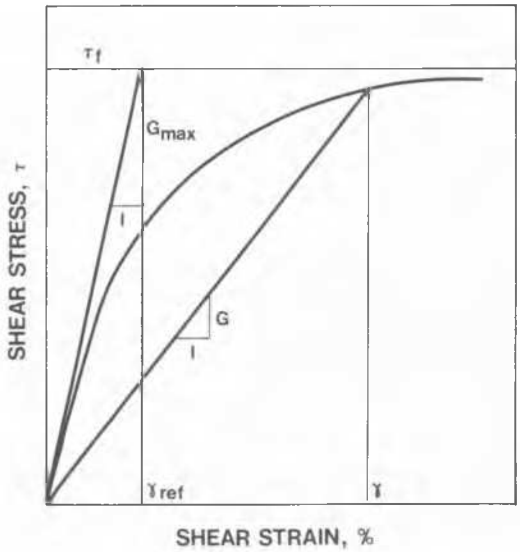

Fig.1 Definition of shear modulus and reference strain

The most important factor influencing shear modulus is strain amplitude. In Fig. 2 are shown results from resonant column tests on clay soils with varying plasticity and water content, (Massarsch 1981b). The secant shear modulus G as defined in Fig. 1 is normalized by its maximum value.

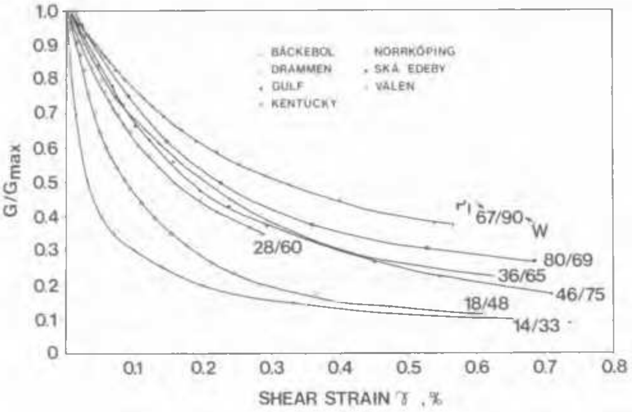

Fig.2 Variation of secant shear modulus with strain amplitude for normally consolidated clays (P_I: plasticity index, W: water content)

The shear modulus decreases significantly already at very small strains. This effect of strain amplitude is more pronounced for soils with low plasticity.

The present paper summarizes results from resonant column tests on clay, published in the literature. A modulus reduction factor is determined at 0.25 per cent shear strain and related to the plasticity index. Finally, an example is given showing how the shear modulus can be estimated for the prediction of excess pore water pressure in clay during pile driving.

LABORATORY INVESTIGATIONS

Resonant column tests on soils from different parts of the world have been studied. Relevant geotechnical parameters are summarized in Table 1 and plotted on the Casagrande plasticity chart, Fig. 3. The soils plot on either side of the A-line.

From the stress-strain curves of the resonant column tests, the shear modulus at 0.25 per cent shear strain can be determined. The ratio of this value and the maximum shear modulus is called the modulus reduction factor, R_F (Table I). The variation of R_F as a function of the plasticity index P_I is shown in Fig. 4.

The shear modulus at 0.25 % shear strain decreases to about 15 to 55 per cent of the maximum value. Although there is some scatter, a significant correlation can be established between R_F and P_I, cf. Fig. 4.

The shear modulus ratio, G/τ_f at 0.25 per cent is also given in Table I. It is interesting to note that at this strain amplitude, the normalized shear modulus varies between 150 and 250. The range of values is much more narrow than that for the ratio of the maximum shear modulus, cf. Table I.

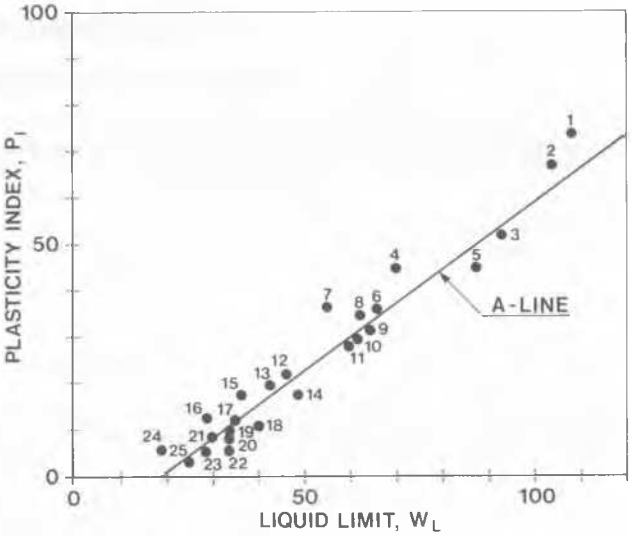

Fig.3 Casagrande plasticity chart showing investigated soils. Numbers refer to Table I.

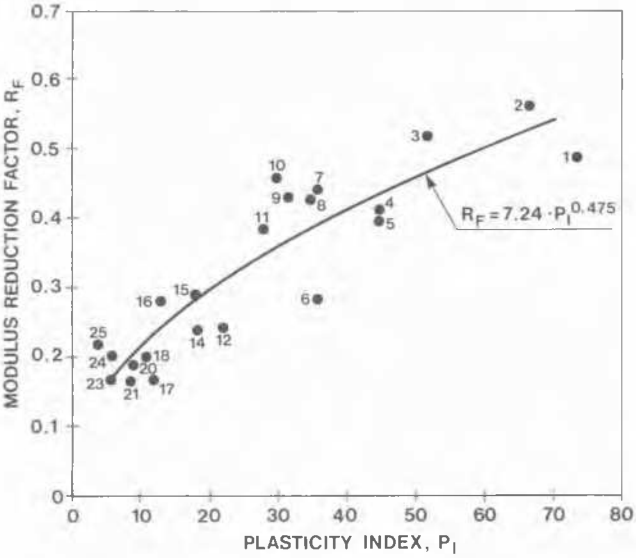

Fig.4 Modulus reduction factor determined at 0.25 % shear strain

EXCESS PORE WATER PRESSURE DURING PILING

Massarsch and Broms (1981) have proposed a semi-empirical relation to predict the excess pore water pressure caused by pile driving in clay, Fig. 5. The excess pore water pressure at distance from the pile can be calculated if the stiffness ratio G/τ_f and the pore pressure parameter A_f are known. It is apparent that the selection of the modulus stiffness ratio has great significance for the calculated excess pore water pressure.

TABLE I

Soil properties and results of resonant column tests

Sample Number (Reference)	Plasticity Index, P_I %	Porosity e	Eff. Confin. Stress σ' kPa	Max. Shear Modulus MPa	G_{max}/τ_f	Modulus Reduction Factor, R_F	$R_F \cdot G_{max}/\tau_f$
1. Gulf (Massarsch, 1981b)	74	2.41	61	8.9	395	0.49	193
2. Välen (Massarsch, 1981b)	67	2.80	48	7.0	376	0.56	211
3. Nevada (Hardin, 1972)	52	1.45	50	34.2	478	0.52	249
4. Ska Edeby (Massarsch, 1981b)	45	2.59	55	14.2	602	0.41	247
5. Bay Mud (Isenhower, 1981)	45	1.05	200	62.0	500	0.40	200
6. Cheeks (Hardin, 1972)	36	0.99	50	67.9	1082	0.28	303
7. Norrköping (Massarsch, 1981b)	36	1.49	49	12.5	568	0.44	250
8. San Francisco (Hardin, 1972)	35	0.85	250	33.1	316	0.43	136
9. Ellsworth (Hardin, 1972)	32	0.68	100	69.2	523	0.43	225
10. Lousiana (Hardin, 1972)	30	1.12	80	9.3	196	0.46	90
11. Bäckebol (Massarsch, 1981b)	28	1.65	51	16.4	683	0.38	260
12. Virginia (Hardin, 1972)	22	0.77	100	77.9	740	0.24	178
13. Rhodes Creek (Hardin & Drnevich 1972)	20	0.98	25	14.4	1150	----	---
14. Drammen (Massarsch, 1981b)	18	1.16	52	24.2	968	0.24	232
15. Air Force Clay (Hardin, 1972)	18	0.63	50	35.9	461	0.29	134
16. Longhorn (Hardin, 1972)	13	0.43	150	126.7	746	0.28	209
17. Kentucky (Massarsch, 1981b)	12	0.76	25	103.7	728	0.17	124
18. Vanceburg (Hardin, 1972)	11	0.59	140	98.6	1064	0.20	213
19. Shanghai (Fang et al (1981)	10	----	---	10.1	455	----	---
20. Kentucky 55 (Hardin, 1972)	9	0.60	50	41.5	667	0.19	127
21. Allen (Hardin, 1972)	9	0.69	50	75.9	1213	0.17	206
22. Lick Creek (Hardin & Drnevich, 1972)	7	0.91	52	26.7	870	----	---
23. Vicksburg (Hardin, 1972)	6	0.67	140	83.7	667	0.17	113
24. Air Force Silt (Hardin, 1972)	6	0.67	50	55.5	1258	0.20	252
25. West Virginia (Hardin, 1972)	4	0.42	100	81.0	746	0.22	164

At the Bäckebol site, the excess pore water pressure was measured at two locations during pile driving (Massarsch and Broms, 1981). In Table II the measured excess pore water pressure is compared with values which were calculated based on in-situ determined undrained shear strength and dynamic shear modulus. The field modulus values are in good agreement with the resonant column test data given in Table I (soil 11).

TABLE II

Comparison between measured and calculated excess pore water pressure.

Distance ρ/r	Pore Pressure Parameter, A_f	G/τ_f	$\Delta u/\tau_f$ Meas.	$\Delta u/\tau_f$ Calc.
3.4	0.5	228	3.03	3.45
6.6	0.9	276	2.70	2.60

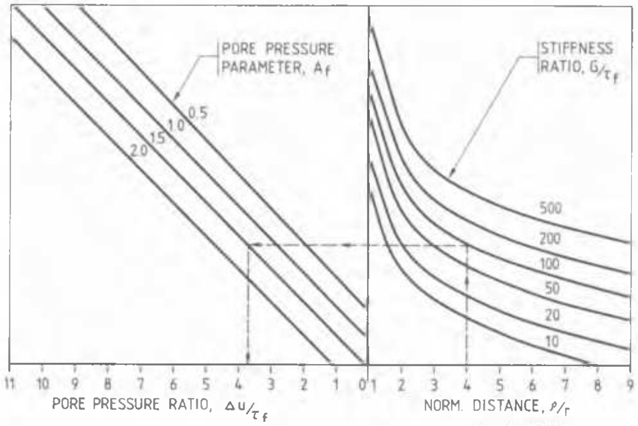

Fig. 5 Variation of excess pore water pressure within the plastic zone during pile driving in clay (Massarsch and Broms, 1981)

CONCLUSIONS

During a resonant column test, at small strain amplitudes, the straining rate is comparable to that of a conventional static laboratory test. The rate of loading appears to have only limited influence on the stress-strain behaviour of clay soils.

Resonant column tests can measure accurately the variation of shear modulus even at very small strain amplitudes. Dynamic tests can be used to study stress-strain behaviour of soils in the laboratory.

The shear modulus decreases significanly even at small strain amplitudes. At 0.25 per cent, the shear modulus corresponds to about 15 to 55 per cent of the maximum value. The reduction of shear modulus is more pronounced in soils with low plasticity.

An equivalent static modulus can be calculated based on dynamic soil tests. The shear modulus at small strain is multiplied by a modulus reduction factor R_F determined at 0.25 per cent strain. The maximum shear modulus can either be measured by dynamic field and laboratory tests, or estimated based on empirical relationships.

The normalized shear modulus G/τ_f at 0.25 % shear strain varies within relatively narrow limits (150 and 250).

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