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SYNOPSIS The shear modulus of a soft, high-plastic clay under dynamic loading conditions was studied. The initial shear modulus was determined by cross-hole and down-hole tests in-situ and by resonant column tests in the laboratory. The reduction of shear modulus with increasing shear strain amplitude was determined in-situ by dynamic loading screw-plate tests and in the laboratory by high amplitude resonant column tests. Field and laboratory test results are compared.

INTRODUCTION

Dynamic deformation characteristics of soft, high-plastic clays were studied in a research project carried out at Chalmers University of Technology, Gothenburg, Sweden, 1974-1979. This paper presents some of the work carried out within the project. For a complete presentation see Andréasson (1979).

In the research project, special emphasize was put on the determination of the shear modulus of the soils and its reduction with increasing shear strain amplitude. Material damping and residual effects of dynamic loadings were also studied.

The experimental work was carried out through field and laboratory tests. In the field, the shear wave velocity was determined according to various test procedures. Screw-plate loading tests, both dynamic, cyclic and static were also performed in the field. Resonant column tests were carried out in the laboratory. Two resonant column devices, designed and built at Chalmers, testing both solid and hollow soil samples, were used in the tests.

SOIL DATA

The tests were carried out at three sites in the Gothenburg region and on samples from these sites. The most extensive programme was performed at a site called Bäckebol II situated 10 km north of the city of Gothenburg in the Göta River valley. The clay at the site is known to be very homogeneous and extends to about 40 m depth.

The uppermost 1 - 1½ m of the soil profile consist of a dry crust followed by a soft, high-plastic grey clay. The clay content is about 60%. From 2 to 10 m depth the natural water content ranges from 80 to 100% while the fall-cone liquid limit is 70 to 90%. The plasticity limit is 30 to 40% and the density varies from 1.49 to 1.60 t/m^3, which corresponds to void ratios of 1.75 to 2.30. The undrained shear strength is relatively constant down to 8 - 9 m depth, around 15 kPa. Below this depth it increases rapidly.

In this paper only tests carried out at the site Bäckebol II and on soil samples from the site will be dealt with.

INITIAL SHEAR MODULUS

The initial or maximum shear modulus, i.e. the shear modulus at very small shear strain amplitudes was determined in the field by shear wave velocity measurements and in the resonant column tests in the laboratory.

In-Situ Shear Wave Velocity

A large number of shear wave velocity measurements were performed within the project. Thus, cross-hole tests were carried out:

- using different spacing between source and receivers
- using steady-state or impulse seismic sources
- using two or three boreholes and
- with or without preboring for sources and receivers

Down-hole tests were performed:

- using one or two receivers
- using different spacing between receivers and
- with or without preboring for receivers

The preferred method for cross-hole tests is shown in Figure 1. Preboring is first made through the dry crust for both the source and the two receivers. The receivers are then installed with iron tubes to the maximum depth

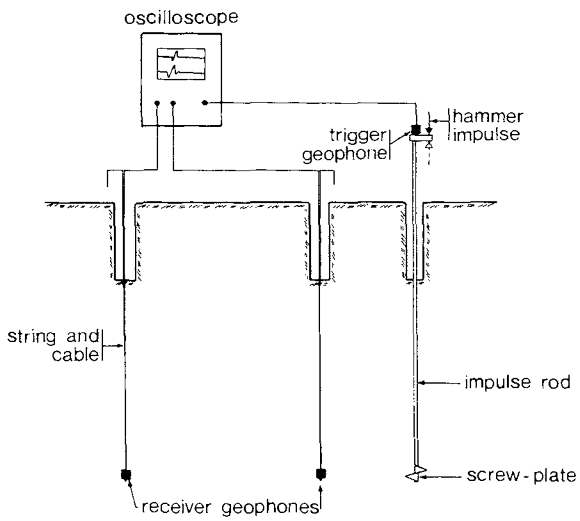

Fig. 1 Cross-hole test procedure

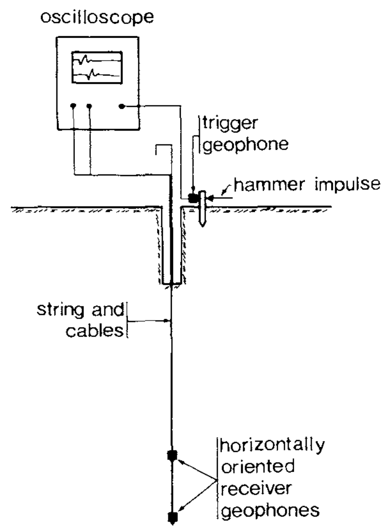

Fig. 2 Down-hole test procedure

to be investigated. Inclinometer measurement of these tubes is necessary to know the exact position of the receivers. The seismic source is a hammer blow on top of a rod with a screw-plate at its tip. Polarized shear waves are produced by hammer blows in both downwards and upwards direction.

After test at maximum depth, the receivers are withdrawn to the next depth to be investigated, and the screw-plate is screwed to the same elevation. After completed cross hole test, the alignment of the impulse rod can be measured by installing an inclinometer profile in the disturbed "hole".

Installation of the receivers without preboring certainly produces a disturbed zone around the receivers. This zone might influence the measured shear wave velocity. However, by measuring the difference in travel time to the two receivers, the influence of these disturbed zones is practically cancelled.

There is always an uncertainty in determing the exact arrival time of the shear wave. One way to elimiate this problem is to use a vibrator instead of a hammer blow as seismic source. By this method, the vibrator frequency is varied, and the vibrations of the two receivers are studied on the oscilloscope screen.

If the two receiver signals are produced on the oscilloscope x- and y-axises, it is possible to very accurately determine the frequencies at which the two signals are in phase and 180 degrees out of phase, an ellipse and a straight line on the oscilloscope screen, respectively. By plotting the vibration frequency vs. "resonance number", the difference in travel time between the two receivers can readily be calculated.

The preferred down-hole test method is shown in Figure 2. After preboring through the dry crust, the two receiver geophones (mounted together) are penetrated by a tube to a depth slightly lower than the maximum depth to be investigated. After withdrawing the installation tube, leaving the two receivers, the strong nylon band is pulled so that the lower geophone stops at its predetermined elevation and the other receiver at a distance above the lower geophone equal to the length of the nylon band between the receivers. The down-hole test at this level is done by a hammer blow on a plate penetrated into the soil. Hammer blows in two directions simplifies the evaluation of travel time. The receivers are then withdrawn successively, for example in one metre-steps, with down-hole shootings at each depth.

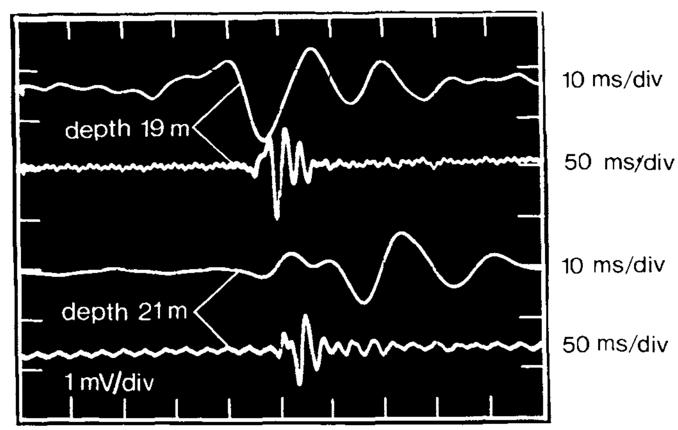

Fig. 3 Oscilloscope recording of a down-hole test

The result of a down-hole shooting according to Figure 2, recorded by the oscilloscope, is shown in Figure 3. In this test the distance between the receivers was two metres. The oscilloscope that was used had the possibility of using delayed sweep. This was done in the test shown in Figure 3. The two lower curves represent the deepest receiver geophone, the lowest of these curves being started by the triggering geophone, while the upper curve starts after a certain time delay. The upper curve is thus an enlargement of a part of the lower curve.

The receiver installation certainly causes a considerable disturbance of the surrounding soil. It is believed, however, that this disturbance has a very small influence on the calculated shear wave velocities. Since the wave velocity in the soil between the two receivers is calculated from the difference in travel time to the two receivers, the effect of disturbance is practically cancelled. The waves from the source to the receivers are believed to travel mainly in intact soil outside the disturbed zone and just locally in the disturbed zone. Comparative tests have verified this assumption.

Resonant Column Test

Two resonant column devices were built within the project. One of these is shown in Figure 4. In a resonant column test, the shear modulus and material damping in the tested soil are determined. To determine the initial shear modulus to be compared with the one determined by shear wave velocity measuremenets in-situ, soil samples from the site were consolidated in the resonant column cell to the estimated in-situ stresses.

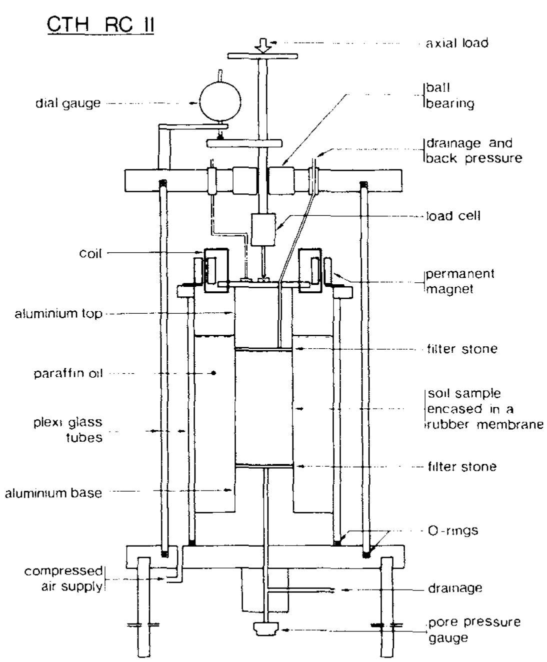

Fig. 4 Resonant column device

The shear modulus and shear wave velocity determined in a resonant column test increases with time. Part of this increase is due to primary consolidation of the soil specimen, but also after completed primary consolidation, the shear wave velocity continues to increase. Soil disturbance from sampling and mounting and thixotrophic behaviour of the soil are believed to be some of the reasons for this time dependent increase in shear wave velocity.

When comparing the resonant column test results with the in-situ shear wave velocities, this time dependent increase must be accounted for. One way of doing this is to extrapolate the laboratory test results to the age of the deposit. This can be done, since, after completed primary consolidation, the shear wave velocity increases about linearily with the logarithm of time.

In Figure 5, the shear wave velocities measured after 1000 minutes of consolidation in the resonant column tests and the values extrapolated to 10 000 years are shown, 10 000 years being the approximate age of the tested soil deposit. The shear wave velocities after 10 000 years of consolidation are presented both extrapolated from the measured increase in shear wave velocity in each test and extrapolated with a mean value of all tests.

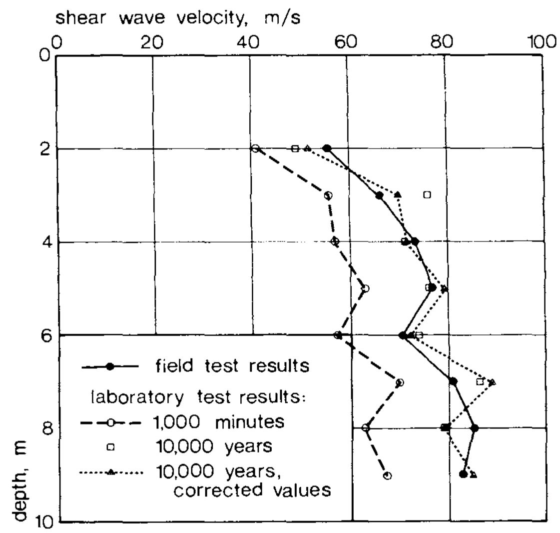

Fig. 5 Shear wave velocities as determined in field and laboratory tests

In Figure 5 the results from the most reliable in-situ shear wave velocity measurements are also presented. The correlation between laboratory and field determined shear wave velocities is very good, when the laboratory data are extrapolated to 10 000 years of consolidation.

MODULUS REDUCTION CURVES

The reduction of shear modulus with increasing shear strain amplitude is a feature of major importance in a dynamic analysis, and many related theories and test results are presented in the literature. In this study, modulus reduction curves were established in-situ by screw-plate loading tests and in the laboratory resonant column tests.

Screw-Plate Loading Tests

Dynamic plate loading tests may be used to determine the shear modulus of soils in-situ. Treating the plate and soil as a lumped parameter system, it is possible to back-calculate the shear modulus from the response of the plate. However, the calculated shear modulus is only valid for the soil just beneath the plate to a depth of one to two plate diameters. One way to overcome this depth limitation is to perform dynamic loading screw-plate tests within a soil mass.

By varying the amplitude of the dynamic load in a plate or screw-plate loading test, it is possible to get information on the influence of shear strain amplitude on the shear modulus of the soil. Naturally, the shear strain amplitude around the screw-plate is far from uniform, and an approximate average shear strain value has to be established.

When analysing the response of the screw-plate under dynamic loading conditions, the lumped parameter method is utilized, i.e. a mass m, a spring with spring constant k_z and a dashpot with damping c is used to replace the actual system.

In a dynamic loading screw-plate test, the frequency at which the displacement of the vibrator is 90 degrees out of phase with the induced force is determined. In case the vibrator was mounted directly on the screw-plate, this frequency would be the undamped natural frequency of the screw-plate. In the actual screw-plate test, however, the vibrator is mounted on top of a rod connected to the screw-plate. A phase lag is produced in the rod. This phase lag has to be accounted for when analysing the system.

The mass value, m, to be used in the analysis is chosen as the sum of the masses of the vibrator, the rod and the screw-plate. These three masses move in somewhat different phases. Due to the relatively low values of frequencies and rod lengths in the tests, the different phases of the masses have not been included in the analysis. The spring constant k_z of the screw-plate is determined from

$$k_z = m\,\omega_n^2 \qquad (1)$$

where ω_n is the undamped natural circular frequency of the screw-plate. When determing ω_n from the test, the phase lag in the rod has to be accounted for. To be able to do this, the damping ratio of the system has to be known. This damping ratio is determined from the shape of the response curve from actual dynamic loading screw-plate tests with constant force amplitude.

The aim of the dynamic loading screw-plate test is to determine the shear modulus of the soil at the level of the screw-plate. The shear modulus is a linear function of the spring constant. For a rigid circular foundation resting on the surface of an elastic half-space, the relation between spring constant in vertical direction and shear modulus, G, is given by

$$k_z = \frac{4Gr_o}{1-\nu} \qquad (2)$$

where r_o is the radius of the foundation and ν is Poisson's ratio.

For a rigid plate within an elastic medium with constant shear modulus, Selvadurai (1976) showed that the spring constant could be calculated from

$$k_z = \frac{32\,(1-\nu)\,Gr_o}{3-4\nu} \qquad (3)$$

There is some doubt as to whether the actual screw-plate in the soil can be treated as a rigid disc in an elastic medium. The soil above the screw-plate is inevitably disturbed by the installation process. The screw-plate is perhaps better represented as an embedded foundation without side friction, as studied by Kaldjian (1969).

Kaldjian determined the increase in spring constant with embedment depth under static loading conditions. The surrounding soil had a constant stiffness and a Poisson's ratio of 0.4. The studied values of embedment depth/ foundation diameter were only 0.1 to 1.8. The increase in spring constant was considerably less than for a buried disc with the same embedment ratios, studied by Butterfield and Banerjee (1971). Extrapolating Kaldjian's results to embedment depths of relevance in this study, and assuming that the results are applicable for $\nu = 0.5$, the spring constant of an embedded foundation is 1.4 to 1.5 times that of a surface footing (with constant shear modulus). The corresponding value for a rigid plate in an elastic medium is 2.0 (Eq. 2 and 3, $\nu = 0.5$).

However, since the dynamic screw-plate tests were mainly made to study the modulus reduction curves, the correct value of the spring constant as a function of shear modulus was not of major importance in this study.

The arrangement of the test equipment in a dynamic loading screw-plate test is shown in Figure 6. In most of the tests, however, the rod was only guided at the lower level, by three horizontal wires, and the vibrator mounted on the rod about 0.2 m above the soil surface.

Before the screw-plate was installed at the desired depth, a 100 mm diameter hole was bored to a depth of about 0.2 m less than the intended screw-plate elevation.

Two types of screw-plate tests were run:

resonance tests and

"sweep" tests

In the resonance tests, the frequency producing a 90 degree phase angle between force and displacement at the vibrator was established. This resonant frequency was determined at increasing levels of dynamic force producing increasing displacements of the screw-plate.

In the "sweep" tests, the displacement amplitude of the screw-plate was determined as a

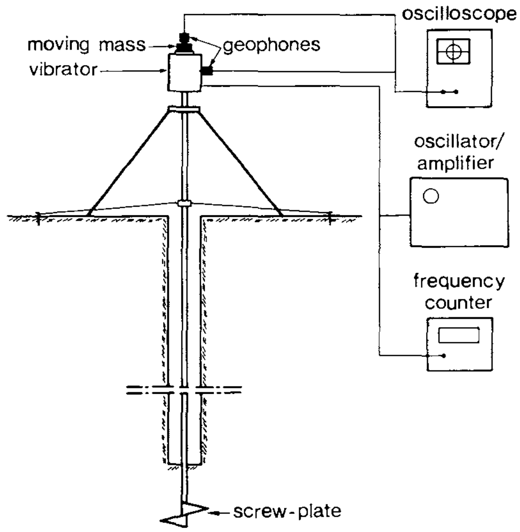

Fig. 6 Dynamic loading screw-plate test, arrangement of equipment

function of the frequency of vibration at a constant force amplitude. The response curve was thus established. This curve was used to determine the damping within the system.

Knowing the system damping, it is possible to calculate the undamped natural frequency of the screw-plate from the resonance test results. The spring constant can then be calculated from Eq. (1) and the shear modulus from the spring constant, as discussed above.

Typical dynamic loading screw-plate test results are shown in Figure 7. The modulus reduction versus relative deformation of the screw-plate are shown for the three tested screw-plate diameters.

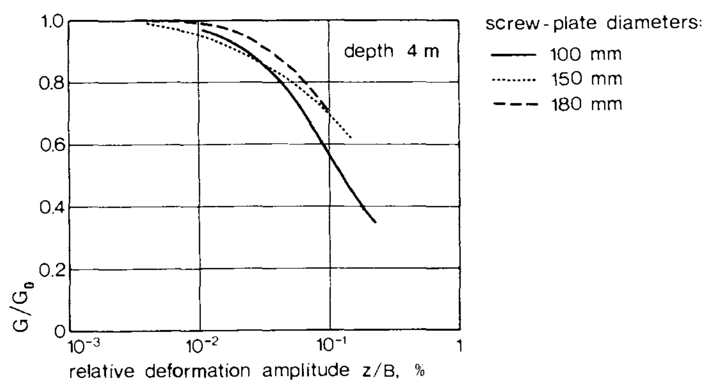

Fig. 7 Normalized shear modulus from dynamic loading screw-plate tests (B=screw-plate diameter)

A total number of 15 dynamic loading screw-plate tests were made. The 150 and 180 mm screw-plate gave quite consistent results while the 100 mm plate showed more varying results.

Assuming the screw-plates to be rigid discs in an elastic medium, the calculated initial shear moduli were only about half the initial moduli determined from shear wave velocity measurements. Assuming them to be embedded foundations, instead, led to initial moduli 20-30% smaller than those deduced from shear wave velocity measurements.

Resonant Column Tests

A series of high amplitude resonant column tests were carried out in the laboratory using the resonant column device shown in Figure 4. The tests were performed to establish the modulus reduction curves to be compared with the in-situ determined modulus reduction curves and to some empirical relationships presented in the literature.

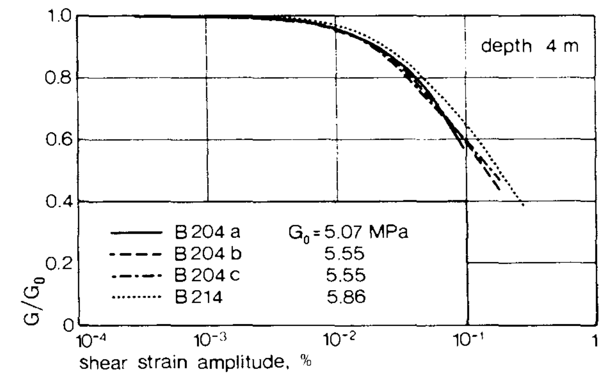

Fig. 8 Results of high amplitude resonant column tests, solid soil samples

Typical test results are shown in Figure 8. The figure shows the results of four tests. Test B 204 a - c represents three successive tests with slightly increasing values of vertical consolidation pressure. (At least one week reconsolidation was allowed between the tests.) Test B 214 was made on a second soil sample. The shear strain amplitude represents the average shear strain in the sample.

The high amplitude resonant column tests were mainly carried out on solid samples but for comparative reasons some tests were also made on hollow samples. No significant difference could be noticed in the test results.

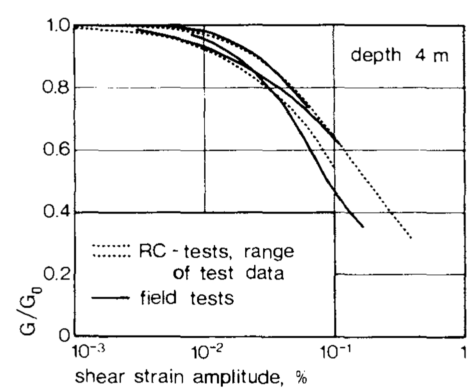

Fig. 9 Modulus reduction curves from field and laboratory tests

In Figure 9, the results of the high amplitude resonant column tests are compared with the results of the in-situ dynamic loading screw-plate tests.

In presenting the screw-plate test results, the relative deformation amplitude of the screw-plate has been converted into a shear strain amplitude. This has been done by simply using a factor of 0.75 on the relative deformation amplitude. This procedure establishs the average shear strain in the soil assuming an influenced soil volume extending to about two plate diameters from the screw-plate centre.

As shown in Figure 9, the correlation between field and laboratory test results is quite good. This was, with a few exceptions, also the results at other investigated depths.

Comparison with Empirical Relationships

The modulus reduction curves established in the field and laboratory tests have been compared to three empirical relationships presented in the literature, namely:

the Seed-Idriss relationship, see Seed and Idriss (1970)

the Hardin-Drnevich method, see Hardin and Drnevich (1972) and

the Ramberg - Osgood method, see e.g. Anderson and Richart (1976).

Without going deeper into these three methods it can be said that the Seed-Idriss relationship represents a lower limit for all clays. The Hardin-Drnevich approach is a general method for all soils based on the concept of a normalized shear strain and a couple of soil constants refered to the actual soil type. In the Ramberg-Osgood method, three parameters are used to adjust the shape and relative position of the modulus reduction curve.

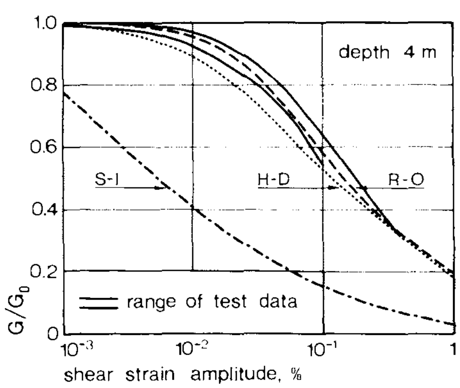

Fig. 10 Laboratory test results and empirical methods to calculate modulus reduction curves

In Figure 10, the resonant column test results are compared to the three empirical methods. As expected, the Seed-Idriss curve falls well below the test results. The Ramberg-Osgood curve, with the three parameters, α, C and R equal to 1.8, 0.5 and 2.5, shows the best correlation with the test results. The Hardin-Drnevich curve, which is not adjusted to the test results, falls slightly below the test results.

CONCLUSIONS

The initial shear modulus determined by shear wave velocity measurements in-situ and resonant column tests in the laboratory were in good correlation, provided that the laboratory test results were extrapolated to a time period corresponding to the age of the soil deposit.

The reduction of shear modulus with increasing shear strain amplitude was studied in the dynamic loading screw-plate tests in-situ and in the high amplitude resonant column tests in the laboratory. Good correlation between field and laboratory test results were achieved, if the shear strain within the influenced soil in the screw-plate tests was calculated as 0.75 times the relative deformation of the screw-plate. The test results were also in good correlation with the Hardin-Drnevich empirical relationship and the Ramberg-Osgood equation with α, C and R equal to 1.8, 0.5 and 2.5.

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