SURFACE WAVE AND DAMPING MEASUREMENTS OF THE GROUND WITH A CORRELATOR

LES MESURES DES ONDES DE SURFACE ET D'AMORTISSEMENT DE LA TERRE EFFECTUEES AU MOYEN D'UNE CORRELATEUR

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SYNOPSIS: Surface wave velocity methods are finding increasing use for determining moduli of the ground in situ at low strain. They can yield shear modulus as a function of depth in a variety of materials. New electronics are making the collection of data much easier. Measurements are made on surface waves generated in the ground by a vibrator. In these experiments a correlator is used to measure the time delay on passage of the waves between a pair of geophones. The signal from one of the geophones is filtered to select the frequency required. An accuracy similar to that of a spectrum analyser is obtained with a fair resolution at low frequencies. Damping is measured by using the instrument in the auto correlation mode. The combined measurements were used to calculate settlements for a site on London Clay. For another site also on London Clay, the values obtained in situ, using surface wave techniques were compared with the values obtained from laboratory samples using the bender elements technique. Provided that the in situ stress state and history are taken into account, the values of very small strain stiffness obtained from laboratory tests are within the experimental scatter of measurements from the surface wave surveys.

INTRODUCTION

Any calculation of ground movements around an engineering structure requires an evaluation of ground stiffness. It is generally recognised that the stress strain behaviour of soils is highly non linear even at strain levels as low as 10^{-4} (Burland 1989). This implies that soil stiffness depends on strain level and can change significantly over the range of strains of interest in civil engineering. Values of stiffness at very small strains, less than 10^{-5}, can be obtained using dynamic testing techniques, in which the deformation properties of the soil are related to elastic wave velocities. A whole class of methods for the determination of in situ stiffness of soil deposits which is becoming increasingly popular is based on field measurements of the shear wave velocity. This is directly related to the shear stiffness of the soil at very small strains, G_{max}, by:

$$G_{max} = \rho V_s^2 \qquad (1)$$

Where ρ is the bulk density and V_s is the shear wave velocity. In situ dynamic tests generally develop strains in the field of the order of 10^{-3} to 10^{-4} and less. In order for these methods to give values of stiffness relevant to many engineering calculations a function must be assumed describing the dependence of soil stiffness on strain level. Powell and Butcher (1991) successfully compared the values of stiffness obtained using a number of in situ loading tests, including pressuremeter and plate loading tests, with in situ geophysical measurements, appropriately corrected for strain level, at a number of clay sites. The underlying assumption of these methods is that the decay of stiffness with strain amplitude observed in the laboratory is similar to that in situ. The laboratory value of stiffness at very small strains may not be equal to the in situ value so that it must be measured directly on site. However Burland (1989) reported successful comparisons between shear moduli obtained from field dynamic surveys (Abbiss,1981) and the initial values of stiffness obtained from undrained triaxial tests on undisturbed samples of London clay. An encouraging comparison between values of very small strain stiffness obtained on a site on London Clay and laboratory data will also be presented in this paper.

Combined measurements of stiffness and damping can be used for the prediction of settlements within the framework of viscoelasticity (Abbiss 1986). Predictions of settlement against time of a loaded pad on London Clay, made from shear wave velocities and in situ damping, are compared with the observed settlement in this paper.

SURFACE WAVE METHODS

Among dynamic field methods the measurement of Rayleigh or surface wave velocities is proving to be a valuable method of insitu site investigation (Powell and Butcher 1991). In the Rayleigh wave experiment seismic waves are generated in a continuous form using a vibrator that oscillates vertically at the surface of the ground. The propagation of the Rayleigh waves at the surface is then detected using two receivers placed at a known distance apart in line with the vibrator. The Rayleigh waves travel with a velocity close to the velocity of shear waves and an amplitude that decays with depth. Most of the energy is in a layer about one wavelength deep. Therefore, for a situation where material properties change with depth, the velocity of Rayleigh waves changes with the frequency of the input excitation because different wavelengths sample material with different average properties. Lower frequencies are associated with deeper data. The surface wave velocity corresponding to each frequency, $V_R(f)$, can be obtained by measuring the phase shift, $\phi(f)$, between the signals from the two receivers:

$$V_R(f) = d\,\frac{2\pi}{\phi(f)}\,f \qquad (2)$$

where d is the known distance between the receivers and f is the frequency in Hertz.

In the method described in the present paper the phase shift between the signals from the two geophones was measured using a correlator (Roesler 1978). The main reasons why the correlator technique was introduced and developed were that it used less expensive electronics than the spectrum analyser, and that it leads to simpler methods of measurement. This instrument displays the cross correlation function between the signals from the two geophones, and incorporates the facility for signal averaging. If the signal from one channel is filtered then the receiving system can be 'tuned' to the frequency of the vibrator. Because noise is random in nature and the cross correlation function detects similarities between signals the instrument can be used effectively to recover the signal from the second geophone with a noisy background, provided that a good quality reference signal from the first geophone is available for comparison. This results in good accuracies in measurement of the phase shift on low frequency signals (f > 12 Hz) necessary to obtain deep data.

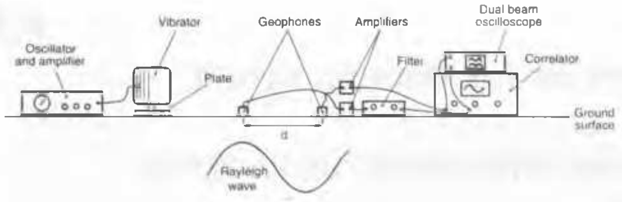

Fig 1 Rayleigh wave velocity measurement with a correlator and filter

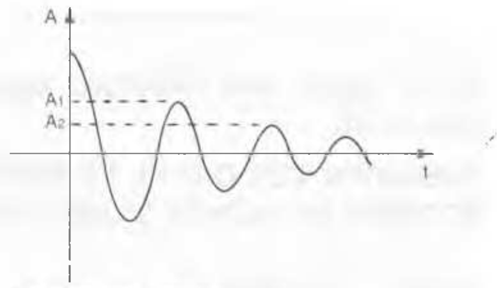

Fig 2 Damped vibration

EXPERIMENTAL TECHNIQUES

Rayleigh wave velocity

The general configuration of the source, receivers and recording equipment used for the surface wave experiment is shown in Figure 1. The waves were generated using a Ling electromagnetic vibrator type 400 connected to a plate resting on the ground. The vibrator was powered by a Ling TPO100 oscillator and power amplifier and was used over the range 8-200 Hz.

The waves were detected by a pair of Sensor Mk 6 geophones placed in line with the vibrator and separated by a measured distance, d. The signal from the geophone nearest to the vibrator was fed through an instrument amplifier, Analogue Device Type AD 524 with a gain of 1000, to a Barr and Stroud filter. This consisted of a high pass and a low pass filter cascaded to act together like a bandpass filter. The tightness or sharpness of filtering was not too great and thus did not blur the time information in the signals. If it had been too sharp there would have been a tendency for the filter to 'ring' independently of the signal that was being filtered (Abbiss 1983). After filtering the signal was led to one of the input channels of a Hewlett Packard 3721A correlator. The other geophone signal was similarly amplified and fed without filtering to the other input of the correlator.

In operation the same frequency was dialled up on the oscillator as on the filter. As discussed above this resulted in a good quality signal from the first geophone against which the output from the other geophone could be compared. The cross correlation function was calculated twice for each frequency used; the first time with the two geophones side by side (no phase shift, reference reading) and a second time at a distance d apart (phase shift equal to ϕ). To check visually the quality of the waveforms generated by the vibrator the signals were monitored at the inputs to the correlator by a dual beam oscilloscope, as shown in figure 1.

The Rayleigh wave velocity as a function of frequency was converted into profiles of Rayleigh wave velocity as a function of depth. The depth was taken as a fraction of the wavelength as described in the literature, either one half where the modulus was effectively constant with depth, or one third if there was a strong increase. (Abbiss 1981, Gazetas 1982). Rayleigh wave velocities were converted into shear wave velocities using the relationship between V_s/V_R and V_p/V_s (White 1965) where V_p is compression wave velocity, and then into moduli using equation 1.

Damping from sinusoidal decay

Damping, was measured in situ by the same apparatus as shown in Figure 1 but without the vibrator. The filtered channel only was used with the instrument operating in the autocorrelation mode. If the ground was struck a blow at the start of a scan, a sinusoidal decay was observed, see Figure 2. This was of excellent quality due to the averaging effect of the autocorrelation. The frequency was determined by the setting of the filter.

The damping D was then calculated from the successive amplitude of peaks in the decay curve A_1 and A_2. D is given by (Abbiss 1986) as:

$$D=\frac{1}{2\pi}\ln\left(\frac{A_1}{A_2}\right) \qquad (3)$$

ASSESSMENT OF TECHNIQUE

The correlator technique was extensively tested on the North Field test site at the BRE, Garston, on boulder clay overlying chalk (Abbiss, 1981). The types of soil at the North field site, obtained from a borehole close to the area where the surveys took place, is shown in figure 3. Several surface wave surveys were carried out in the North Field site to assess the influence of various parameters on the observed values of Rayleigh wave velocities. In particular in this work, tests were carried out to define the optimum number of averages to be taken with the instrument to find a compromise between the stability of the readings and the speed of the survey. Also different spacings of the receivers were used.

The results obtained from these surveys are shown in figure 4 in terms of Rayleigh wave velocity versus depth. The Rayleigh wave velocity was found to increase approximately linearly with depth, similar to that found in previous experiments (Abbiss 1981). This, with an assumption of constant density, leads to a profile of shear modulus which increases quadratically with depth from a value of about 25 MPa at the surface to about 500 MPa at a depth of 15m. Even if with hindsight it is possible to detect a greater scatter of the data points at critical depths, see figure 3, the test results did not provide enough evidence to locate the change of strata. This may be because in a situation where softer layers are underlain by stiffer layers the Rayleigh wave averages out the properties.

The results obtained using the correlator and the filter were compared with those obtained using the standard technique where a spectrum analyser is used to measure the phase shift between the signals from the two geophones, see figure 5. The spectrum analyser allows very accurate measurements of the phase shift of the main Fourier component of the signal to be made even at low frequencies where the quality of the signal deteriorates. The lowest value of frequency at which measurements could be made satisfactorily using the spectrum analyser was about 8 Hz, corresponding to a depth of 20 m.

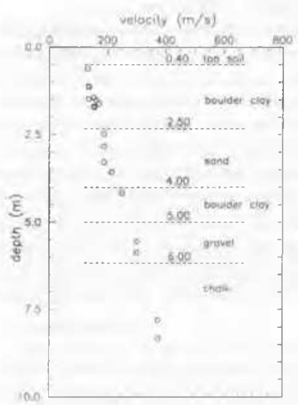

Fig 3 Soils and Rayleigh wave velocities, North Field

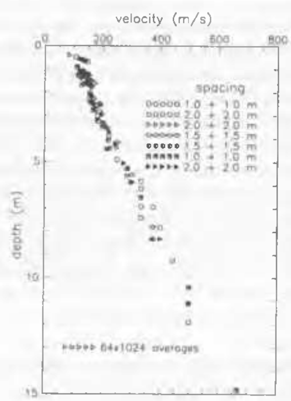

Fig 4 Rayleigh wave velocities, North Field

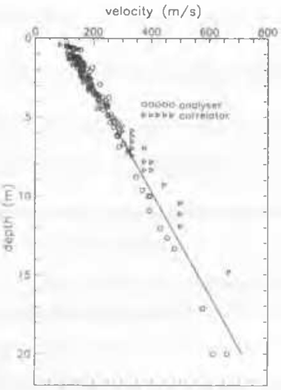

Fig 5 Comparison of correlator and spectrum analyser (Rayleigh waves)

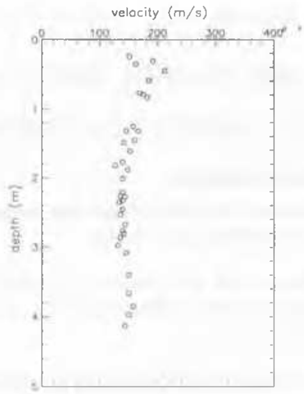

Fig 6 Rayleigh wave velocity against depth, Canons Park

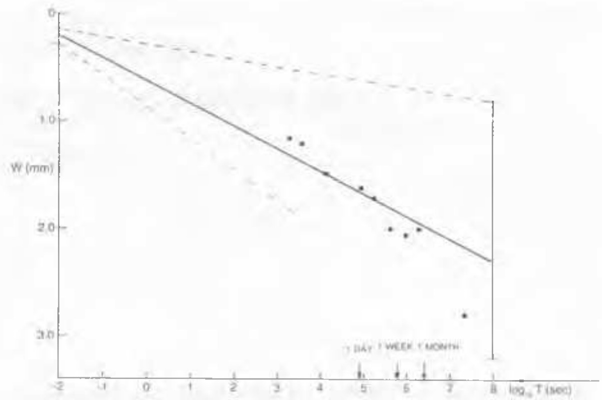

Fig 7 Calculated and observed settlement of the pad, Canons Park

The data obtained using the correlator are generally more dispersed and tend to give lower values of velocity near the surface and higher values at depth, if compared to the values obtained using the spectrum analyser. Also the lowest value of frequency at which measurements could be made satisfactorily using the correlator was about 12 Hz corresponding to a penetration of about 15 m. The overall agreement between the results from the two techniques was considered satisfactory as indicated by the data in figure 5.

SETTLEMENTS OF A TEST PAD ON LONDON CLAY

Data were taken at the BRE test site at Canons Park where the subsoil consists of London clay almost to the surface. The profile of shear wave velocity versus depth resulting from these surveys is shown in figure 6. Here the distribution of shear wave velocity with depth is quite different from the North field site, with a stiffer layer at the surface and relatively constant values beneath. The transition between shallow stiffer layers and deeper softer layers is clearly indicated. At Canons Park this transition seems to correspond to that between a superficial layer of gravel and the top of the London Clay which at these shallow depths is reworked.

Damping was measured as described previously. A range of frequencies was chosen with an average of 40 Hz. No trend with frequency was observed. A value of D of 4±1% was obtained. On the basis of the damping and stiffness measurements described above a class B prediction, carried out at the same time as the observations, was made for a 2 m x 2 m concrete pad, cast 0.150 m below the surface. The four corners of the pad were provided with levelling studs and the levels measured relative to a datum ten metres away. Readings were taken with a high precision level fitted a parallel plate micrometer and using an invar staff. The pad was loaded with a standard refuse skip loaded with sand to a pressure of 24.5 kPa and the resulting settlements measured over suitable intervals of time. The settlement of the centre of the pad at these times is shown in figure 7. After 2 weeks the pad had settled 2 mm.

The method used for the prediction of the settlements of the pad is based on the generalised theory of viscoelasticity and has been successfully used to predict settlements of foundations on stiff clays and weak rocks, for conditions far from failure (Abbiss, 1986). The elastic modulus obtained from the surface wave surveys is used in the chart from Brown and Gibson (1972) to find the elastic settlement plotted at the start at $\log(t) = -2$, the approximate period of the surface wave. The slope of the settlement line at the initial point on the time plot is then found from $d(\ln\varepsilon)/d\ln(t) = 4D/2\pi$ (Abbiss and Lewin 1990). The appropriate value of D, for the strain under the pad, was obtained from the 's' curve of damping fitted to the measured D of 4% at known strain (Abbiss 1986). A linear plot was drawn from the initial point, with this slope on the graph of settlement against log(t). As can be seen in figure 7 the prediction is close to the observed settlement after two weeks. The error bars shown are largely due to uncertainties in the values of D and so this measurement is where the improvement in accuracy is needed.

COMPARISON OF FIELD AND LABORATORY DATA

A third site investigated was on London clay at Chattenden, Kent, about 45 km east of central London. From one borehole close to the area where the dynamic surveys took place, the London clay was found to extend from the surface to depths larger than 30 m. Two surface wave surveys were carried out at Chattenden and the results are summarised in figure 8. The profile of shear wave velocity versus depth is characteristic of an overconsolidated clay, with the stiffness practically constant with depth after stiff superficial values. The 1990 data is higher and may have been affected by the stiff upper layer of dry clay.

Parallel to the field surveys dynamic measurements of very small strain stiffness were carried out on samples of London clay from Chattenden in the laboratory using piezoceramic bender elements of the type developed at the Norwegian Geotechnical Institute (Dyvick and Madshus, 1985). These are electromechanical transducers that can be located at each end of a triaxial specimen which transmit and receive shear pulses through the specimen. The tests result consists essentially of the travel time for the shear wave to propagate along the length of the specimen. From this travel time the shear wave velocity, V_s, can be calculated and in turn the shear modulus obtained using equation 1. The shear wave amplitude is not constant along the sample due to both geomechanical and material damping. The maximum shear strain near the transmitter is estimated to be about 10^{-5} (Dyvick and Madshus, 1986).

Based on the results of bender element tests on both reconstituted and undisturbed samples of London clay retrieved from the site at Chattenden the relationship found to describe the dependence of the very small strain stiffness of the soil on state is given by:

$$\frac{G_{max}}{p_r} = A\left(\frac{p'}{p_r}\right)^n R_p^m \qquad (4)$$

where p_r is a reference pressure of 1kPa, introduced to render the relationship between shear modulus and mean effective stress p' non dimensional. A, n and m are non dimensional constants. R_p is the ratio p'_{max}/p' with p'_{max} the maximum previous mean effective stress. For the London clay at Chattenden A = 407, n = 0.76 and m = 0.25. (Viggiani 1992)

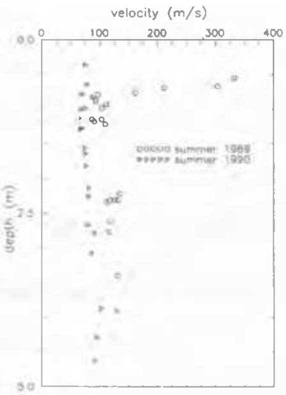

Fig 8 Surface wave velocities at Chattenden

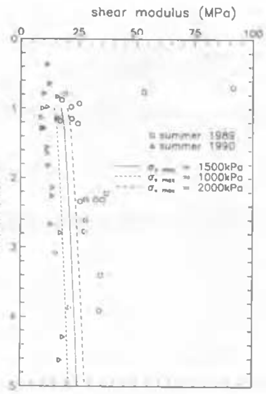

Fig 9 Comparison of field and laboratory data

In order to compare the values of G_{max} predicted by equation 4 with those obtained from the in situ dynamic surveys a knowledge of the stress state and history in situ are required. Here $p' = (1+2K_0)\sigma'_v/3$ with σ'_v the vertical effective stress and K_0 the coefficient of earth pressure at rest. The vertical effective stress can be readily determined from density measurements and a knowledge of the position of the water table, at a depth of about 1.3 m below the surface. No specific data on the depth of overburden removed by erosion or on the values of K_0 were available at Chattenden. An estimate of the reduction of vertical effective stress due to erosion, $\Delta\sigma_v' = 1500$ kPa, was obtained from data by Skempton (1961) relative to a site whose geology resembles very closely the geology at Chattenden. With this value of maximum overburden a profile of OCR (σ'_{vmax}/σ'_v) with depth was obtained and also values of K_0 at different depths. The values of OCR were determined following the method proposed by Wroth (1975). This is no more than a rough estimate of the stress state of the ground but can be used to assess whether the values of G_{max} obtained in situ compare with those obtained in the laboratory.

In figure 9 the values of G_{max} predicted by equation 4 are compared with the results of the site dynamic surveys. The calculations were carried out using a reduction of vertical effective stress due to erosion $\Delta\sigma_v' = 1000$, 1500 and 2000 kPa but the prediction was not dramatically influenced by the value of the maximum overburden. The values of very small strain stiffness predicted on the basis of the laboratory results are within the experimental scatter of the field data.

CONCLUSIONS

Accurate phase shift measurements are possible with a correlator and a filter in the determination of surface wave velocities with a vibrator. The standard deviation is nearly as good as that with a spectrum analyser with a potential saving in cost and is a step towards using simpler methods. It has the additional advantage of being capable of measuring the damping in situ, thus supplying the rest of the information needed to make prediction of settlements from viscoelastic theory. With reasonable assumptions of the in situ stress state and history, the small strain moduli obtained in the laboratory using the bender elements technique are within the experimental scatter of measurements made by this method.

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