Continuous Surface Wave (CSW) analysis

Ground engineers often require evaluation of deformation properties of soils and rocks for the prediction of ground movements. Traditionally this has been achieved through *in-situ* loading tests and laboratory tests. In the last 50 years, surface wave surveying has been developed to determine 1D profiles of the shear wave velocity (V_s), and hence ground stiffness, to about 30 m below the ground. The Continuous Surface Wave (CSW) technique was the first such technique to be developed for engineering purposes, and a is rapid and relatively inexpensive site investigation tool. CSW has been successfully used to produce stiffness parameters in many projects, *e.g.* in the design of cut-and-cover tunnels and retaining walls, over closed landfills, and in the assessment of ground treatment.

Principles of operation

The shear modulus *G* is becoming a valuable parameter for ground stiffness assessment and is readily determined through seismic investigation. The advantage of using a seismic method is that it is not affected either by insertion effects or by sampling disturbance. The stress-strain relationship exhibited by weak rock and soils is non-linear, such that high stiffnesses result from small strains. For a strain of less than 0.001% the stiffness becomes constant and is therefore the maximum stiffness possible (G_{max}). Seismic methods apply strains of approximately this magnitude. For intermediate strains (0.001-0.1 %) the stiffness is proportional to the strain and for larger strains (>0.1%) the soil exhibits plastic behaviour and the stiffness becomes less sensitive to strain and approaches a minimum value as the material is brought to failure.

Field observations of ground deformations around full-scale structures can be predicted using non-linear models where the initial strains are very small. These discoveries have closed the gap between static and (small strain) dynamic measurements of stiffness such as seismic observations, and have made seismic investigation a viable method of determining ground stiffness. Field tests of the geophysical approach to ground stiffness determination have demonstrated that the values resulting are often more useful to engineers than those determined by traditional invasive means.

Field technique

The equipment used is highly portable and each deployment requires a level site area of just a few square metres. The system consists of a variable-frequency vibrator source and a string of two or more connected geophones (Figure 1). In most soils, Rayleigh waves travel at a depth of between a half and a third of a wavelength, so a reduction in vibrator source frequency forces the effective depth of surface waves to increase. A variable-frequency Rayleigh signal generator is placed on the ground surface and energised at a number of known frequencies in the approximate range 5-600 Hz.

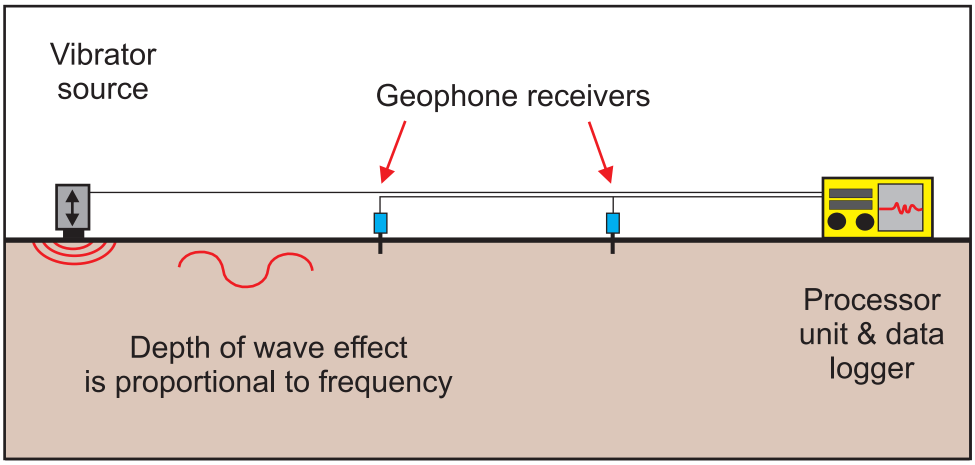

Figure 1: Survey setup for Continuous Surface Wave ground stiffness determination, after Matthews *et al.* (1996).

The number and distribution of profiles acquired is determined by the Client's sampling requirements and also by the nature of the ground cover. As a general rule, acquisition of each profile requires an hour after set-up, with approximately eight tests being achievable in a day.

Interpretation

Knowing the frequency of the source (f), the distance between the geophones (d) and the measured phase angle ($\o$), the wavelength (λ) and Rayleigh wave velocity (V_R) may be calculated as follows:

$$V_R = f.\lambda \quad \text{where} \quad \lambda = (360/\o).d$$

This allows the variation in Rayleigh wave velocity with depth to be determined. V_R is typically 5% slower than the shear wave velocity (V_S) in most soils, with the exact percentage dependent on Poisson's Ratio, so a correction to the Rayleigh wave velocity provides values for V_S. This velocity can then be converted to provide values for G_{max} using the bulk density of the sub-surface material.

The information obtained through this technique takes the form of a plot of shear modulus *vs.* depth (Figure 2). Note that the measured stiffness values are the greatest (G_{max}) at minimum strain levels. Depths are assigned for each test frequency by scaling the wavelength appropriately.

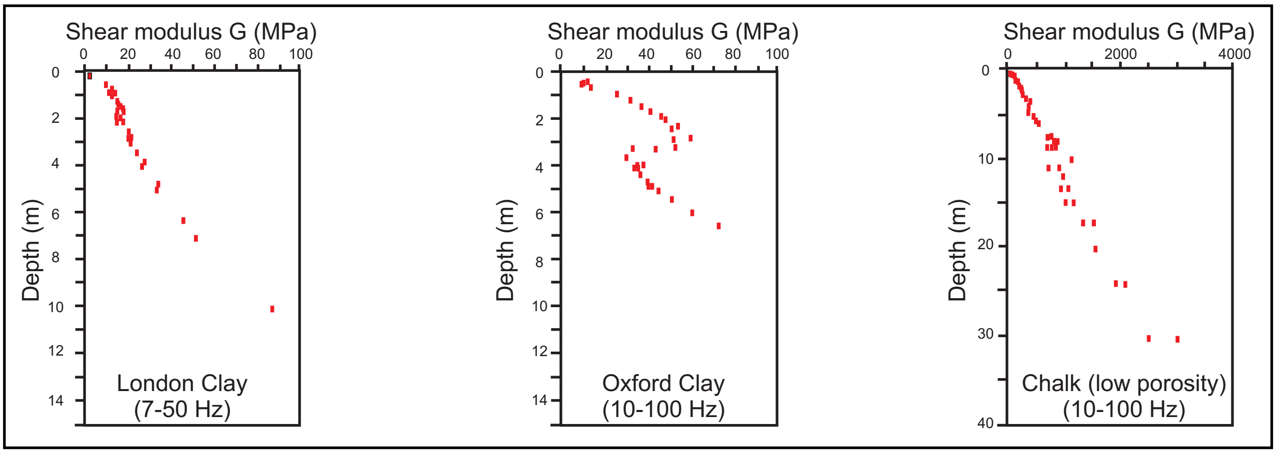

Figure 2: Profiles of shear modulus vs depth for sites underlain by London Clay, Oxford Clay and Chalk, after Matthews *et al*. (1996).

More complex inversion methods can be used to produce layered models of G_{max}. However, such methods are only appropriate for data of good quality and where the geology is suitable.

Applicability

Because this technique studies the propagation of surface waves, it works best on level ground. Made ground, bedrock and unconsolidated sediments are all suited to the technique; very dry sands are less suitable. The total attainable profile depth varies with soil type; as a rough guide penetrations range between 10-30 m. Because the technique relies on detection of low frequency seismic waves, sites where sources of low-frequency mechanical noise are present (*e.g.* mechanical excavators, motorways, heavy industrial plants) and cannot be temporarily suspended should be avoided. Further details of the CSW method are given by Reynolds (2011).

References

Matthews, M.C., Hope, V.S. and Clayton, C.R.I. 1996. The use of surface waves in the determination of ground stiffness profiles. *Proc. Instn. Civ. Engrs. Geotech. Engng.*, **119**(April):84-95.

Reynolds, J.M. 2011. *An Introduction to Applied and Environmental Geophysics*. John Wiley & Sons Ltd, Chichester, 2nd ed., 712 pp.

