

Measure for measure

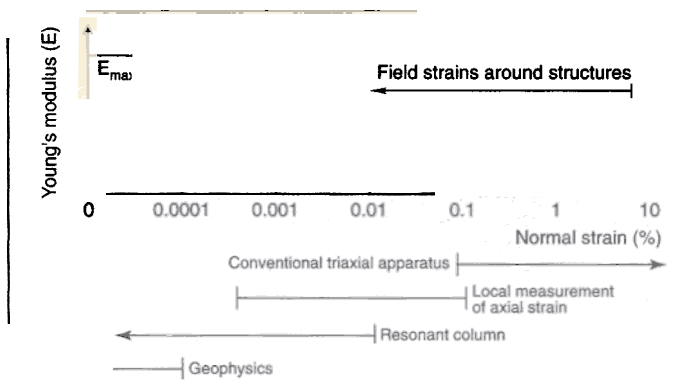
The shear modulus of soil and rock at very small strains, G_{max} , is very useful for finite element analysis. Patrick Hooker examines some methods to evaluate this fundamental soil parameter.

During the late 1980s and early 1990s, dynamic soil stiffness was measured in the laboratory using small strain resonant column apparatus. Investigators were struck by the similarity of these dynamic moduli to static moduli back-analysed from movements around real static structures like retaining walls and excavations.

They then realised the differences in moduli measured in the past between static tests (like the conventional triaxial) and dynam-

ic tests (like the resonant column) were related to strain level – ie one test measured small strain moduli and the other large strain moduli, not to the fact that one test was “dynamic” and the other “static”.

More recently, the value of G_{max} (the value of the shear modulus at very small strains) has been treated as a fundamental soil property that is particularly useful in finite element modelling. This means there is much interest in the measurement of G_{max} both in the laboratory and field.



In the laboratory, small strain stiffness can be measured using local measurements of axial strains either with Hall Effect local strain measurement or LVDT based devices. For very small strain measurements the resonant column or bender element methods can be used.

In the field, seismic methods can be used for measuring the value of G_{max} . A range of seismic tests have been developed commercially, including the seismic cone penetration test (SCPT),

cross-hole and down-hole shear wave velocity measurement, and the surface wave (Rayleigh Wave) methods of SASW (spectral analysis of surface waves) that uses a hammer as the seismic source and CSW (continuous surface wave) that uses a frequency-controlled vibrator as the seismic source. The field seismic methods can be divided into borehole methods and surface methods.

Dr Patrick Hooker is managing director of GDS Instruments.

Laboratory methods

Bender elements

Measurement of soil stiffness at very small strains in the laboratory is difficult because of limited resolution and accuracy of load and displacement measuring devices.

The bender element system allows measurement of G_{max} by measuring the velocity of shear wave transmission through a test specimen.

Bender elements are made from strips of piezoelectric material constructed in such a way that the application of an electrical voltage causes the element to bend in one direction or the other. Similarly, a bender element device that is subjected to bending generates a small

voltage which can be measured.

By using an element as a transmitter at one end of a test specimen and another element as a receiver at the other end of the test specimen, shear waves can be transmitted and recorded. The shear waves created in this manner generate very small strains and the transmission time of the shear wave can be used to calculate the value of G_{max} .

Recently, it has been shown that the bender element can be wired so that it can also transmit and receive P-waves and thus gives the potential for direct measurement of the constrained modulus at very small strains. Adding bender elements to a triaxial testing system enables routine modulus measurements as a test proceeds.

GDS Instruments and GeoDelft have developed a cost-effective bender element system. The elements are available as inserts, so they can be integrated with new GDS systems or fitted into existing systems (including those not manufactured by GDS).

Three different types of element pairs are available: S-Wave only, P-Wave only (high power) and combined S- and P-wave. Each set of element pairs comprises a “source” and a “receiver” element.

The bender elements are encapsulated and then mounted in “inserts” which are fixed into either a pedestal or topcap. Bender elements are delicate instruments and occasionally

need replacing, which is a simple matter of swapping the damaged element for a new one.

The system of inserts makes the GDS system cheap to buy and maintain as well as reducing the “down-time” for replacement of a damaged element.

Resonant column

The resonant column apparatus gives the capability of measuring the shear modulus and damping ratio for a cylindrical test specimen.

One end of the test specimen is fixed and the other end is excited with a very small sinusoidal rotational displacement. The excitation is swept through a range of frequencies and the frequency at which resonance occurs is identified.

From a knowledge of the specimen and the resonant frequency, the value of the wave propagation velocity and hence shear modulus (G) can be found. The excitation is set to induce very small strains and therefore it is the value of G_{max} that is calculated.

GDS Instruments has developed a novel resonant column apparatus enabling tests to be carried out at a range of confining pressures from low to very high (up to 25MPa).

The apparatus also has the option of temperature control from -30°C to $+50^{\circ}\text{C}$. In addition to the normal torsional mode of excitation the GDS resonant column can also use a vertical bending mode of excitation.

The system is fully supported by



GDSLAB software to allow the selection of excitation mode under computer control.

Small-strain hollow cylinder The new GDS low cost small-strain hollow cylinder apparatus is designed to be capable of testing at very small axial strains (down to 0.00004%).

A hollow cylinder apparatus means it is possible to control the magnitude and direction of the three principal stresses. Studies can, for example, be made of:

- the anisotropy of soil samples
- the effects of principal stress rotation
- the effects of intermediate principal stress.

The system can apply a uniquely



In situ methods

Continuous surface wave system

The GDS continuous surface wave system (CSWS) is non-invasive and makes use of Rayleigh waves which are constrained to propagate along the surface within a zone approximately one wavelength deep.

In ground where the stiffness changes with depth these elastic waves are dispersive – they travel at a velocity that is dependent upon frequency or wavelength.

The CSWS uses a frequency controlled vibrator to regulate the frequency of these surface waves, permitting a dispersion curve (velocity against frequency or wavelength) to be captured easily.

By using the theory of elasticity, shear wave velocity and shear modulus G can be determined from these velocity measurements – the velocity measurements are made at very small strains and therefore it is the parameter G_{max} that is measured.

Thus the system enables a shear stiffness-depth profile to be determined up to 10m (in clays) and 30m (in some granular soils and weak rocks) without the need to provide a borehole.



Horizontally polarised shear wave source for borehole applications

GDS Instruments is a partner in a consortium developing horizontally polarised shear wave source for borehole applications (Horsa) technology.

The programme is funded by the Department of Trade and Industry's LINK programme Sensor and Sensor Systems for Industrial Applications' (S3IA).

Horsa is a versatile exploration tool for the determination of anisotropy and dynamic elastic moduli. Operating in air-filled or water-filled boreholes, either vertical or inclined, Horsa is a new

generation of seismic sources designed to meet engineers' needs. The Horsa unit operates from a battery powered supply and its small size and light weight enables surveys to be undertaken in remote locations. Surveys can be carried out in boreholes to 100m depth.

Encompassing both a vertically and horizontally polarised shear wave source, the Horsa sonde can be used with the GDS touch-screen field control system in borehole based seismic investigations for up-hole, cross-hole

and tomography investigations.

Seismic investigation allows in situ determination of compressional and shear wave velocities. These velocities can be combined with density data to calculate formation elastic parameters such as Poisson's ratio, Young's modulus, bulk modulus and shear modulus. The elastic parameters are important in many geotechnical engineering problems, determination of seismic response and in mine development.

wide range of stress paths on the test specimen. The loading systems are computer controlled and strains can be measured directly on the test specimen. These strains can also be servo-controlled. Studies can therefore be made under the following test conditions:

- stress paths in p,q,b,a stress space
- plane strain
- simple shear
- very small shear strain.

Standard and advanced triaxial tests can also be carried out in the apparatus on standard solid cylindrical test specimen, including:

- K-zero consolidation and swelling
- continuous linear stress paths.

Two versions of the system are available, a dynamic and a lower cost "static" version. The dynamic version has all the functionality of a dynamic hollow cylinder apparatus at a price approaching that of a standard dynamic triaxial system.

Researchers at Southampton University have used the hollow cylinder apparatus to accurately model principal stress rotation for use in finite element analysis of the deformation of railway track bed material.

Track bed materials under moving wheel loads (ie trains) are subjected to complex stress conditions that cannot be reproduced using conventional triaxial testing, although the results from

these tests have largely determined design methods for pavement structures.

Hollow cylinder testing showed that principal stress rotation had a significant effect on the rate of permanent deformation, pore pressure build-up and the stiffness of a silty clay under undrained cyclic loading.

By investigating the significance of principal stress rotation on different types of geomaterials in pavement structures, Chris Clayton and Hannes Gräbe of the university's Geotechnical Research Group say the design life of railway foundations should be more accurately predicted.



Expertise & Innovation in Ground Investigation

Ritchies is one of the UK's leading ground investigation and geo-technical contractors operating from regional centres in Kilsyth, Wigan, Clevedon and Dublin. The company continues to grow nationally offering a comprehensive ground investigation service to consultants and clients in a variety of construction sectors including building and property, rail, highways, public health, environmental, industrial and marine engineering.

- Soils boring
- Rock drilling and coring
- Window sampling
- Environmental monitoring
- Trial pitting
- Water wells
- Instrumentation installation
- Overwater investigations
- UKAS laboratory testing and reporting

Ritchies
 Scotland
 Glasgow
 Tel: 01236 467000
 Fax: 01236 467030
 South
 Clevedon
 Tel: 01275 875 338
 Fax: 01275 870 076

North
 Wigan
 Tel: 01942 248 882
 Fax: 01942 248 890
 Ireland
 Dublin
 Tel: +00 353 1431 0540
 Fax: +00 353 1431 0539



<http://www.edmund-nuttall.co.uk>