Applying modern measures

Laboratory testing is fundamental to soil mechanics design. Over the next four pages *Ground Engineering* looks at developments in laboratory testing viewed from different sectors of the testing industry. The feature starts with a report from **Bruce Menzies**, director of GDS Instruments, on development of high-tech testing equipment.

Anyone who has been in a traditional soils laboratory or one dealing with rock mechanics will immediately feel a rapport with the cartoon in **Figure 1**. Heath Robinson drew his "Intricate machine for an accurate compression test" more than 50 years ago. The astonishing truth is that in some labs little has changed to the present day. This is somewhat surprising considering the powerful twin engines driving equipment development. On the one hand, outstanding applied research over the past three decades; on the other, the much trumpeted exponential advances in electronic instrumentation and computing.

Some examples of laboratory equipment development

Probably the most sophisticated tests routinely carried out in soils labs are U-U and C-U triaxial, step loading consolidation and direct shear. Advanced versions of these tests are: effective stress (measurement of pore pressure), multi-stage, stress path, and dynamic triaxial; continuous consolidation tests; and ring shear, respectively.

Advanced triaxial

Triaxial testing can now include multi-stage and stress path testing under computer control. For stiff soils, local strain measurement and mid-plane pore pressure measurement can also be carried out. The use of bender elements can also provide small strain stiffness. With modern direct current brushless servo motors and motor control electronics, dynamic tests can now be carried out by direct screw drives.

In the past, hydraulic or pneumatic actuators were required which were difficult to operate under closed loop control. The dynamic triaxial apparatus enables the build-up of pore pressure with number of cycles to be quickly studied. As shown in **Figure 3**, new triaxial cells are now available which were inspired by Bishop and Wesley's stress path cell. Instead of being actuated hydraulically through the base, the cell is actuated through the base by a stepping motor and screw drive.

The cell top and base are fixed together by internal rods making a rigid construction. The cell chamber is external and can be raised and lowered by a counterweight system. Test specimens can be placed in the cell with precise alignment. Transducer access ports are built-in so that local strain transducers and a mid-plane pore pressure probe can be used.

Happily, many of the applications of modern electronics and computers to triaxial testing have escaped from universities and research establishments. Systems are now available for commercial testing labs. For the system shown in **Figure 4**, for example, tests are selected from a menu which includes B_0, isotropic consolidation, U-U, C-U, C-D and Multistage. For a commercial operator, the advantages of such a system are:

- ● tests controlled automatically overnight and during weekends and holidays;
- ● automatic data logging and data presentation including plotting Mohr's circles;
- ● international data presentation standards built into the software;
- ● familiar and user-friendly operator interface presented in Windows.

Continuous consolidation

Continuous consolidation such as constant rate of strain, constant rate of loading and controlled hydraulic gradient tests can now be automatically carried out. This is important because the flow of pore water into or out of the test specimen is more or less steady. The test therefore proceeds at a constant rate and can be completed relatively rapidly. This is in contrast to the conventional step loading test where the hydraulic gradient causing the pore water flow is itself reduced by the flow. This gives rise to an exponential decay in flow rate and so tests are very slow with poor productivity.

Under computer automation, controlled hydraulic gradient tests can be carried out for back-pressured oedometers. For both consolidation and triaxial testing, this solves the perennial problem of what drained testing rate to use – here the soil permeability "decides" the testing rate with the user setting an acceptable excess pore pressure (**Figure 5**).

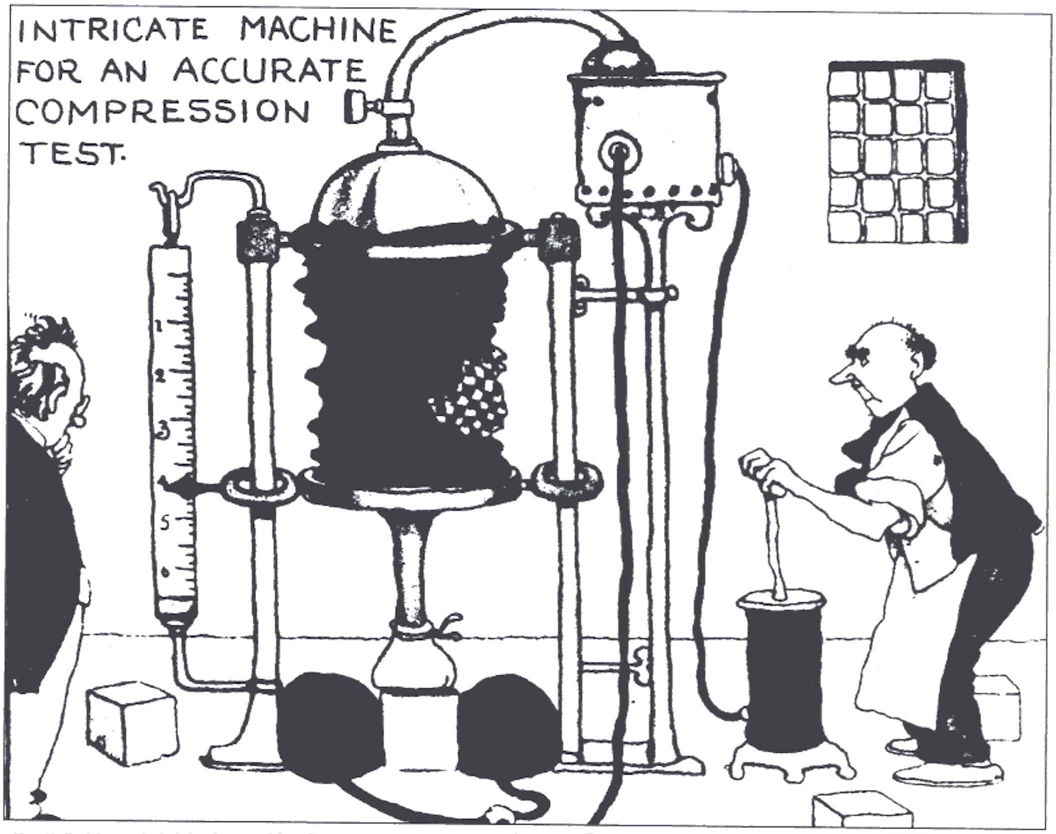
Milestones in research over the past three decades

Stress path dependency of soil moduli

In the UK during the 1960s and 1970s the major discovery was that soil, unlike other civil engineering materials, has properties dependent on loading pattern or "stress path". Deformation moduli are not unique material constants but vary according to the actual stress path.

This understanding led Professor Alan Bishop of Imperial College and his research student Laurie Wesley to develop a new kind of hydraulic triaxial cell in which the stress paths encountered in practice could be followed. Complex loadings could be applied which simulated real geological, construction and in-service conditions where vertical and horizontal stresses both change at the same time.

It might be thought that this was some esoteric pursuit by dedicated researchers of arcane and small effect. Far from it.



Heath Robinson's Intricate machine for an accurate compression test (Figure 1).

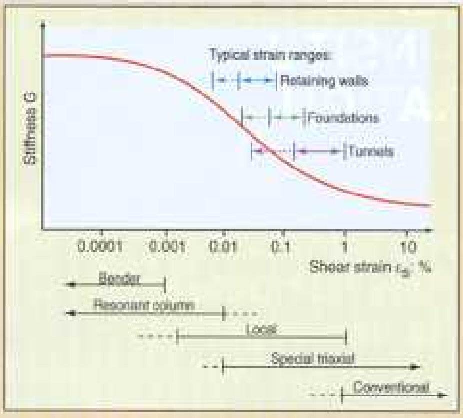
Table 1. Example of settlement calculations:

Circular foundation in London Clay at Bradwell (Simons 1971)

Settlement type	Conventional method	Stress path method
Immediate	32.7mm	17.2mm
Consolidation	109.0mm	40.9mm
Total	141.7mm	58.1mm

Table 2. Measurement of soil stiffness (Jardine et al 1984)

Soil type	Shear strength Su	Eu(0.1%)/Eu(0.01%)	Error%
North Sea Clay	122	0.185	540
Ham River Sand	1085	0.518	193
London Clay	123	0.371	270
Upper Chalk	1350	0.723	138



LEFT: Idealised stiffness-strain behaviour of most soils.

Professor Noel Simons of Surrey University showed that for a circular foundation in London Clay at Bradwell, conventional methods overestimated stress path settlement by a staggering 240%.

Small strain stiffness of soil controlling ground movements

During the 1980s researchers were puzzled by the huge difference between ground stiffness measured in the lab and that back-analysed from finite element modelling of real structures like foundations, retaining walls and tunnels.

Dr Richard Jardine and Professor John Burland at Imperial College realised that conventional methods of strain measurement in the triaxial test included bedding errors which exaggerated the amount of measured deformation, giving artificially low stiffness readings. They used local strain transducers inside the triaxial cell to measure soil deformations directly on the test specimen. The results were spectacular. As shown in the table, these were not small errors of a few percent – some over 500% were measured.

Seismic means for measuring operational ground stiffness

During the late 1980s and early 1990s, soil stiffness was being measured in the lab using various resonant column apparatus. Investigators were struck by the similarity of these dynamic moduli to stiffnesses back-analysed from movements around real static structures. They then realised the differences measured in the past between dynamic and static moduli were related to strain level – not that one test was "dynamic" and the other "static" (**Figure 2**).

Somewhat unexpectedly, then, the seismic-like resonant column test measured stiffnesses close to field static operational values. This encouraged researchers to look again at seismic methods for measuring soil and rock stiffnesses insitu, which gave rise to the commercial development of Spectral Analysis of Surface Waves and Continuous Surface Wave methods for measuring the upper bound to operational ground stiffness – a classic example of how lab testing can lead to the development of field testing equipment.

Ring shear

Ring shear tests provide the complete shear stress-displacement relationship for soil. This is important because soil is a strain-softening material. This means that after the peak value is reached, shearing resistance reduces to a residual value. The same thing can happen on a slip surface where strain varies. Mobilised strength therefore also varies around the slip. Where strain exceeds that required to mobilise peak strength, load is shed to pre-peak regions causing progressive failure. An index gauging this effect is Skempton's Residual Factor. The most widely used ring shear apparatus was developed by Professor Eddie Bromhead of Kingston University.

Summary

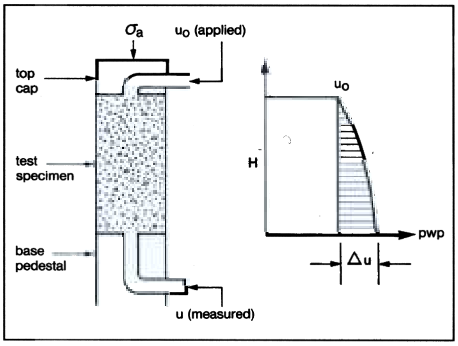
The technological advances of the recent past include:

- computer control as well as data logging and presentation via user-friendly software.
- microprocessor closed loop control of set or programmed test parameters. For example triaxial cell pressure can be regulated using the screw pump principle shown in **Figure 6**.
- new transducers eg local strain (**Figure 7**), mid-plane pore pressure.

The future

The advances in geotechnical knowledge, electronics and computing mean that research discoveries of just a few years ago are already rapidly influencing developments in laboratory testing. The interaction between lab and field testing is also stronger. For example, local strain measurement in the triaxial test and Continuous Surface Wave geophysics can provide upper and lower bounds to operational ground stiffness. This remarkable partnership is possible because of the development of new transducers and very powerful portable computers.

ABOVE: Figure 4. Triaxial Automated System for commercial labs.



ABOVE: Figure 3. New motorised "stress path" triaxial cell.
RIGHT: Figure 5. Hydraulic gradient in a top drained triaxial or consolidation test specimen.
BELOW: Figure 6. Schematic diagram of screw pump principle.

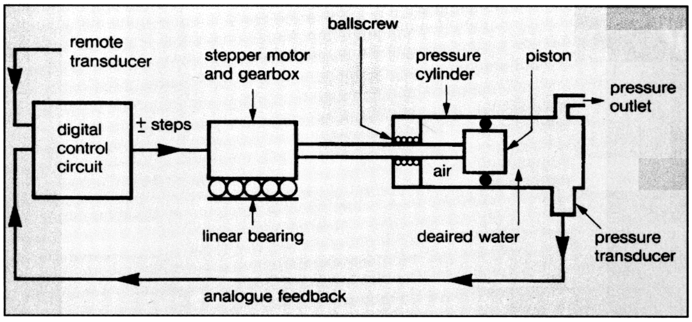


Figure 7. Triaxial test specimen with axial and radial Hall Effect local strain transducers.

References

Simons, NE (1971). "The stress path method of settlement analysis applied to London clay". Stress-strain behaviour of soils. Ed. RHG Parry. Proc Roscoe Mem Symp 241-252.

Bishop, AW and Wesley, LD (1975). "A hydraulic triaxial apparatus for controlled stress path testing". Geotechnique 25, No 4, 657-670.

Jardine, RJ; Symes MJ and Burland, JB (1984). "The measurement of soil stiffness in the triaxial apparatus". Geotechnique 34, No.3, 323-340.

Clayton, CRI; Gordon, MA and Matthews, MC (1994). "Measurements of stiffness of soils and weak rocks using small strain laboratory testing and geophysics". Proc. Int. Symp. on Pre-failue Deformation Characteristics of Geomaterials. Balkema, Rotterdam, 1, 229-234.