PART 1: KEY TERMINOLOGY AND ENGINEERING PARAMETERS FOR GEOTECHNICAL ENGINEERING.

Prepared by the GDS Instruments Technical Team

Overview: This new 5 part series has been written to explain the hardware, software and instrumentation used in the testing of soil and rock. The series comprises of 5 chapters (see below). The series is aimed at people interested in gaining a better understanding of geotechnical laboratory equipment.

1. **Key Terminology and Engineering Parameters for Geotechnical Engineering,**
2. Principles of Instrumentation Measurement – Error, Accuracy and Resolution,
3. Calibration of Geotechnical Instruments
4. Selecting Ideal Transducer Range,
5. Principles of Testing Machine Control Feedback.

INTRODUCTION

Soils: Key terminology and engineering parameters (Simons et al., 2002)

Typically, soil comprises a skeleton of soil grains in frictional contact with each other forming an open-packed structure (loose/soft) or close-packed structure (dense/hard). The soil particles may be microscopic in the case of *clays* (which may range in hardness from *soft* to *stiff*), just visible in the case of *silts*, and clearly visible in the case of *sands* (which may range in *density* from *loose* to *dense*, and in *particle size* from *fine* to *coarse*) and the larger particle sized *gravels*. The distribution of particle size is called *grading*. The *soil skeleton*, which can also be *cemented*, forms an interstitial system of connecting spaces or *pores*. The pores in the soil will usually contain some moisture even in *unsaturated soils*. The flow of pore water can be restricted by the small size of the pores and degree of saturation thus giving rise to low *permeability* k particularly in clays. During construction, for saturated soils the change in load or *total stress* σ is shared between the soil structure and the *pore pressure* u. The time-dependent flow of water in soil under applied load is referred to as *consolidation* (pore water flowing out of a loaded zone) or *swelling* (pore water flowing into an unloaded zone) and is the means whereby total stress change is transferred from pore pressure to structural loading of the soil skeleton as measured by *effective stress* $\sigma' = \sigma - u$, the parameter that uniquely controls all deformation in soils. It is this time-dependency that gives saturated clays their unique behaviour whereby they have a *short term* or *undrained strength* s_u that is different from the *long term* or *drained strength* s_d. This is why soil supported structures (e.g. foundations) and soil structures (e.g. embankments and cuttings) have *short term stability* and *long term stability* e.g. why Victorian-era railway cuttings in England failed half a century after construction. The maximum capacity of the soil skeleton to support load is called the *shear strength* because soil fails in shear. This strength depends on the frictional nature of the inter-particle contact and is measured by the coefficient of friction or *angle of shearing resistance* ϕ', and by the constant, *cohesion* c', with respect to effective stress as designated by the prime notation thus $'$. The deformability of the soil skeleton is measured by elastic theory deformation moduli such as *Young's modulus* E, *Poisson's ratio* v and *Shear modulus* G. Because of formation history such as deposition by wind or water, soil insitu possesses *fabric* or geometric orientation of particles that gives rise to *anisotropy* i.e. different properties in different directions.

Soil can be geologically loaded to a *maximum past pressure* or *preconsolidation pressure*. This pre-load constitutes a *yield point*. At stresses less than yield the soil behaves elastically i.e. the strains are nearly recoverable. At stresses more than yield the soil behaves plastically i.e. the strains are not recoverable and the mathematical *theory of plasticity* is sometimes used to describe the post-yield soil behaviour e.g. in finding the *bearing capacity* of footings and piles. *Stress distributions*, however, can be described generally using the mathematical *theory of elasticity* that is also used for the prediction of vertical movement such as *settlement* (downward) or *heave* (upwards).

Soil properties can be studied and parameters measured in a variety of tests. The most common and most useful test is the *triaxial test* that is carried out in the laboratory so that test conditions can be carefully controlled. Other important laboratory test equipment are the *resonant column apparatus* that measures maximum shear modulus, the *hollow cylinder apparatus* that is an element test and can apply rotation of *principle stresses* (e.g. as pertain under moving wheel loads), and the *ring shear apparatus* that measures *residual shear strength* on an established shear surface (e.g. such as may control stability on natural slopes that have previously slipped).

Soil may be characterised by plasticity index tests that give rise to a range of indices including *Liquid Limit*, *Plastic Limit* and *Liquidity Index*. These indices have been correlated empirically with soil parameters such as undrained Young's modulus.

Field tests include penetration testing such as the *Standard Penetration Test (SPT)* (split spoon hammered into the ground) and the *Cone Penetration Test (CPT)* (cone pushed into the ground by hydraulic means) that require empirical correlation with soil parameters. Other field testing equipment includes the *pressuremeter* that expands a cylindrical casing against the sides of a borehole (the *Camkometer* – for "Cambridge k-zero meter" – is a self-boring pressuremeter) and the *dilatometer* which expands a spade-shaped diaphragm after pushing the dilatometer into the ground.

The widespread availability of commercial finite element stress analysis software has concentrated attention on measuring soil parameters, particularly ground stiffness. This has led increasingly to the use of *seismic* test apparatus to measure *shear wave velocity*. *Up-hole*, *down-hole* and *cross-hole* methods use boreholes. The *seismic cone* penetration test uses a hammer at the surface to produce vibrations detected by a receiver in the cone. Using a hammer or a frequency-controlled vibrator at the ground surface generates *surface waves*. These include *Rayleigh waves* that travel parallel to the ground surface to a depth of about one wave length thus testing the soil in the mass (i.e. including the effects of fissuring and jointing) in a non-invasive way. The resulting ground vibrations are detected by an array of vertically polarised sensors or *geophones*. From surface wave tests, shear wave velocity is correlated with *wavelength* and this data can be interpreted to give *stiffness-depth profiles*. Shear wave velocity measurements can be used to *characterise* soils as well as to provide useful data for estimating sampling disturbance.

It is important to make the distinction between a *soil property* and a *soil parameter*. A soil property is independent of test type and can be used to characterise soils (e.g. shear wave velocity). A soil parameter is dependent on test type (e.g. undrained strength) but is useful for design purposes, particularly when correlated with field performance of full scale works.

Rocks: properties, terminology and behaviour (Matthews et al., 2008). Introduction: the main differences between soil and rock

It is important to distinguish between soil and rock because their properties are very different and so their engineering behaviour is different too. This has given rise to different disciplines for analysing stability and settlement of ground. Civil engineers, on the one hand, learn soil mechanics where ground is idealised as a continuum within which failure mechanisms like slip surfaces can spontaneously develop (e.g. in a cut slope or an embankment foundation slipping on a circular arc or some other mechanism) as well as pre-exist. Pore water pressure is dealt with implicitly in terms of effective stress, the difference between total stress and pore water pressure, which is a measure of the loading transmitted by the structural skeleton of soil grains. Engineering geologists and mining engineers, on the other hand, learn rock mechanics where ground is regarded as an assembly of rigid blocks that slide (or not) along existing frictional joints or surfaces that may or may not be orientated to predispose a collapse of the rock mass e.g. by sliding out of the side of an excavation like a tunnel, cutting or quarry. Water pressures from water filling the joints are dealt with as hydrostatic force vectors.

Soil is made up of particles of weathered rock that are microscopic in the case of clays or visible to the naked eye in the case of sands. Not surprisingly, soil behaviour is governed by this particulate character. Unlike rocks where particles are bound by being crystalline or cemented, in soils the particles are free to move by rolling, crushing and changing their packed structure from loose to dense (consolidation or compaction) or dense to loose (swelling or dilantancy). The interstitial voids or pores between particles interconnect and provide flow paths for ground water to flow through (very slowly in the case of clays, more rapidly in the case of sands). Engineering behaviour and the key properties of soil strength and stiffness are therefore governed by the sizes and distribution of sizes of particles and their density of packing. Conversely, rock behaviour is governed by discontinuities which separate the rock mass into an assembly of rigid blocks. The overall engineering performance of the rock mass will be dictated by the number and distribution of the discontinuities and crucially their compressibility which is very much lower than the intact rock (in contrast to soil where compressibility of fissures is not so markedly lower than the intact soil).

It is therefore the structure of geomaterials (soil and rock) that controls the engineering behaviour of the ground. Take for example a landslip. In the case of soil, if the bedding of the soil follows the down slope of a potential slip, long translational slips can occur. If the soil structure is random or the material is homogeneous, failure can occur on a circular arc with a rotational slip. In the case of rock, however, slips or topples can occur only if the jointed block structure allows a feasible mechanism.

Cohesive or fine-grained soils such as clays are highly time-dependent in their behaviour. For example the recovery of pore pressures in some Victorian railway cuttings in London clay took over half a century, leading ultimately to collapse. Rocks, on the other hand, are not time-dependent in their behaviour over the life of a civil engineering structure. Rocks may change their properties due to weathering but the time scale involved will normally greatly exceed the design life of a foundation (typically 50-90 years).

Key terminology in rock mechanics

The engineering behaviour of rocks is almost always overwhelmingly conditioned by the rock discontinuities such as joints, faults and fractures. These discontinuities are planes of weakness across which there is little or no tensile strength. Mechanisms of excavation collapses, land slips and bearing capacity failures will be feasible or not and will activate depending on the extent, pattern and types of discontinuity present in the rock mass. The mass compressibility of the rock is a combination of the compressibility of the intact rock and the compressibility of the joints. Clearly, the greater the extent of the joints and the lower their compressibility, the more the joint properties will dominate overall mass behaviour.

Stiffness of Rock Masses

For civil engineers, it is more usual to express the deformability of rock (and soil too) in terms of the material stiffness, Young's Modulus, *E*, the ratio of stress increment to consequent strain increment in a uniaxial or triaxial test. Stiffness has units of stress, MPa. Compressibilty is the inverse of stiffness and has units of MPa^{-1}.

The way discontinuities can dominate stiffness of rock masses can be illustrated in Fig. 1. Here, Matthews (1993) used the formulation of Hobbs (1975) to carry out a parametric study of the effect on mass stiffness of fracture (or joint or discontinuity) frequency and fracture thickness or "aperture". In Fig. 1, the subscripts correlation is "m" for "mass" (i.e. including joints or fractures), "j" for "joint" (i.e. joint properties only), and "i" for "intact" (i.e. intact or parent rock only).

The case with the joints open to 1.0mm, aligned perpendicular to the direction of the applied load is shown in Fig. 1 (a). This represents a geometry often found in chalk. It will be seen from Fig. 1 (a) that as the modulus of the joint approaches that of the intact material (i.e. $E_j/E_i = 0.5$ in Fig. 1 (a) the number of joints has little effect on the ratio of mass modulus to intact modulus.

The implication is that that for the softer type of materials such as soils the joint system does not cause an appreciable difference between the mass modulus and the intact modulus. The most significant feature of this model, however, is the extremely rapid drop in E_m/E_i with the introduction of only a few (1 to 8) fractures per metre when the ratio of E_j/E_i is less than 0.005 (or ½%). When the fracture frequency exceeds about 10 per metre, the mass modulus becomes relatively insensitive to increasing number of joints.

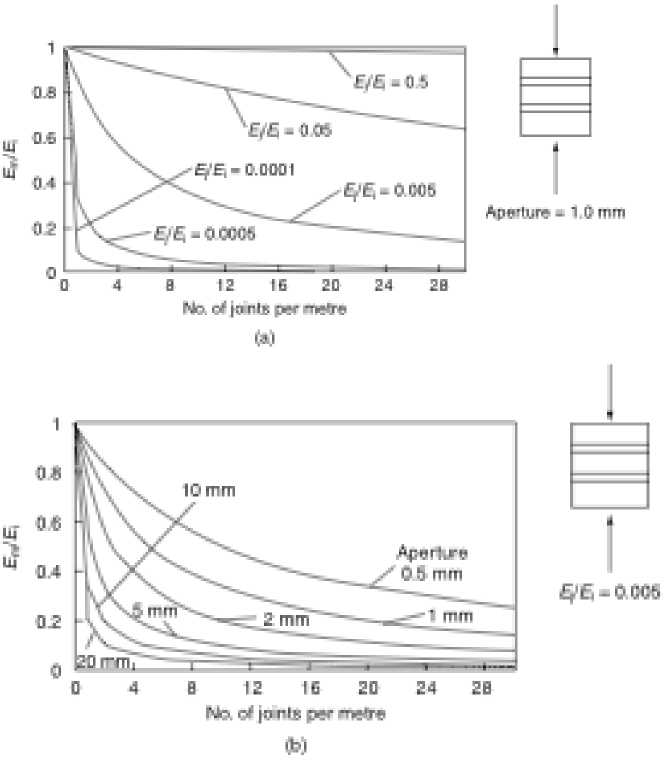

Fig. 1 (a) Variation in the ratio of mass stiffness to intact stiffness with fracture frequency for fractures with different stiffnesses; (b) variation in the ratio of mass stiffness to intact stiffness with fracture frequency for fractures with different apertures (Matthews et al., 2008).

The relationships shown in Fig. 1 (a) assume a constant joint aperture of 1.0mm. If the ratio E_j/E_i is kept constant, and the aperture varied, the set of curves shown in Fig. 1 (b) results. Not surprisingly, the greater the aperture, the greater the mass compressibility.

References:

Simons, N. E., Menzies, B. K. and Matthews, M. C. (2002). *A short course in geotechnical site investigation*. Thomas Telford, London, 353p.

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