SOILS ELASTIC PARAMETERS : A PARALLEL BETWEEN IN SITU AND LABORATORY MEASUREMENTS

François Huot(*) and Ludovic Baron(+)

(*) formerly Laboratoire de mécanique des sols, Ecole Polytechnique Fédérale de Lausanne; now (+).
(+) Institut de Géophysique, Université de Lausanne, CH-1015 Lausanne.

INTRODUCTION

Measuring geotechnical parameters in a borehole and in particular the elastic properties is a goal for many geophysicists. This technique would have several advantages : it would give valuable information for geotechnical engineering design, such as a continuous set of data with depth, showing soft and stiff zones. It would be more representative than laboratory testing because soils would be less altered by sampling and it would be faster than usual laboratory techniques. To show that it is possible to measure geotechnical data by logging a borehole, comparison must be made between in situ and laboratory testing.

Biot (1956) wrote the equations of propagation of elastic waves in a biphasic porous medium; he showed the existence of a second compressional wave, the slow P wave, due to the two phases' different stiffness, which was proved by Plona (1980). Further developments can be found (Nakagawa et al, 1997). From Domenico (1977), at an infinite frequency, the bulk compressibility is expressed as :

$$K_b = \frac{\left[v_p^2 \rho_b \left(1 - \frac{\rho_f \phi}{\rho_m \kappa} \right) - \frac{4}{3} v_s^2 \rho_b \left(1 - \frac{\phi \rho_f}{\kappa \rho_b} \right) \right] (K_f - \phi (K_f - K_m)) - K_m K_f \left(\frac{\rho_b \phi}{\kappa \rho_f} - 1 - 2 \frac{\phi}{\kappa} \right)}{\left[v_p^2 \rho_b \left(1 - \frac{\rho_f \phi}{\rho_m \kappa} \right) - \frac{4}{3} v_s^2 \rho_b \left(1 - \frac{\phi \rho_f}{\kappa \rho_b} \right) \right] \frac{K_f}{K_m} + \phi K_m + K_f \left(\frac{2\phi}{\kappa} - 1 - \phi \right)}$$

$$\mu = \rho_b v_s^2 \left(1 - \frac{\phi \rho_f}{\kappa \rho_b} \right)$$

v_p	P wave velocity (m/s)	ϕ	Porosity
v_s	S wave velocity (m/s)	κ	Coupling factor
ρ_b	Bulk density (kg/m ³)	K_b	Bulk compressibility (Pa)
ρ_f	Fluid density (kg/m ³)	K_m	Matrix compressibility (Pa)
ρ_m	Matrix density (kg/m ³)	K_f	Fluid compressibility (Pa)
μ	Shear modulus (Pa)		

Standard numerical values $2.18 \cdot 10^3$ MPa for pure water, $36 \cdot 10^3$ MPa for quartz matrix are used ; the coupling factor between solid and fluid phases is within 1 (no coupling) and infinite (monophasic medium).

LABORATORY TESTING

Laboratory testing is performed on samples taken from the logged borehole. Emphasis must be laid on the fact that to make good quality measurements in laboratory it is necessary to obtain soil specimens as close to in situ conditions as possible (Atkinson et al, 1992; Sasitharan et al, 1994). One of the goal of the study is to perform most tests on the same sample in an environment close to in situ conditions to be able to compare laboratory and in situ testing. Two major phases are involved in a soil core laboratory testing : sample preparation and triaxial testing. In the first phase, all the initial geometrical and mass characteristics are measured on the specimen ; sample is then placed in a triaxial testing system, in which it is submitted to a stress state close to the theoretical one in situ (i.e. pore pressure (u) and principal stresses ($\sigma_1, \sigma_{2,3}$) related to position of phreatic level and depth of specimen).

Laboratory testing

Standard laboratory testing techniques (Head, 1986) allow to measure many of the soils characteristics involved in Biot's equation : ρ_b is found by measuring height, diameter and weight of the sample. Weight changes of sample before and after drying in an oven (102°C) leads to the degree of saturation (S_r) and then to porosity (ϕ). ρ_s is calculated by measuring mass and volume of a powdered sample in a picnometre. ρ_f is supposed to be constant and is not measured ($\rho_f = 1000 \text{ kg/m}^3$).

Triaxial testing

The coupling factor (κ) is dependent of the permeability (K) which can be monitored by applying a different pressure at each end of the sample and by measuring the outflow induced. Pressures must be small enough (a few percents of total pore pressure) to consider that change has no influence on the soil structure. Elastic moduli at small strain are the last characteristics to be measured. They can be determined by different ways, among which are small strain cyclic loading and wave propagation through the sample. Moduli are strongly dependent on the strain amplitude at which they are calculated (Alarcon-Guzman et al, 1989; Ishibashi and Zhang, 1993) : to make a comparison between moduli measured by the two ways one has to make measurements in the same range of strain.

Monitoring ultrasonic wave velocities requires a specific triaxial cell similar to the one described by Nakagawa (Nakagawa et al, 1996) but with different S-wave transducer, made with « bender elements » that create a true S wave while bending into the specimen (Shirley, 1978; Bates, 1989). It has been shown that S waves are generated and received at the tip of each transducer (Huot, 1995). Wave speeds are calculated by measuring transit time and distance between transducers ; axial strain created ($\epsilon = \Delta l/l$) is in the range of 10^{-10} .

Small strain under cyclic loading are measured with Hall effect sensors and load cell is used for deviatoric stress determination. They allow the determination of elastic moduli for strains in the range 10^{-4} to 10^{-5} . This strain amplitude is much larger than the case of wave propagation but it corresponds to the elastic range defined by most authors (Hicher, 1996).

Once all the soil's characteristics are known, it is possible to compare moduli given by wave speed and moduli given by triaxial testing, in order to establish the relation between sonic in situ measurements and standard laboratory testing.

BOREHOLE MEASUREMENTS

Logging tools are employed in order to find in situ material properties entering in Biot's equation. Due to the logging procedure, results are only available in the saturated zone. Bulk density and porosity are respectively measured in the borehole with slim tools : a gamma-gamma probe (Mount Sopris KLP 2780 with a 5 mCu source) and a neutron probe (Mount Sopris LLP-2676 with a 1 Cu source). Specific equations are used to convert CPS in g/cm^3 for density and to find porosity under the water table, based on measurements on calibration blocks of known density and porosity (Aluminium, lucite and sand with different porosity). As many subsurface boreholes have irregular shape, a hole diameter correction has to be done for both logs (obtained with the caliper probe Mount Sopris CLP 2380).

P wave velocity (v_p) is calculated from the Δt log using a slim sonic probe (Mount Sopris OLP 2182) and v_s , when possible (i.e. $v_s > v_f$ the P wave velocity in the fluid), from the full wave sonic log. Otherwise, this velocity can be calculated from the Stoneley wave velocity and frequency (Mari et al., 1997). A second, more accurate, full wave form sonic probe (OYO P-S Suspension log) able to generate stronger S wave is also used to measure P and S velocities in soft formations.

A value of the coupling factor κ along the borehole is obtained with the four electrical logs : 8'', 16'', 32'', 64'' (Probe Mount Sopris JLP 2780) and with a fluid resistivity log (Probe Mount Sopris NLP 2280) using the formula (Brown, 1980) :

$$\kappa = \phi \frac{R_t}{R_w}$$

Where R_w is the fluid resistivity (Ohm.m) and R_t the bulk resistivity (Ohm.m).

A natural gamma ray log (probe Mount Sopris HLP 2375) enables the estimate of the clay content in soft formations. All the above logs should be modified in regard to this content which could strongly affect the results.

A sharp calibration of these environmental logging tools is necessary to get accurate results. Actually, the most important difficulty encountered while logging in soft formation is the instability of the borehole. For this reason all these logs should be performed through a PVC casing which requires a correction for the casing effect on the log data and/or the effect of the hole diameter. Some tools have already been calibrated for different type of PVC casings (gamma-gamma, neutron, natural gamma ray probes) but in the case of wave speeds v_p and v_s , it is almost impossible to compensate the effect of the casing.

Continuous elastic information from a borehole should help engineers in their design practice, producing more information than the classical discrete sampling procedure and testing.

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