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Assessment of anisotropic elastic parameters of saturated clay measured in triaxial apparatus: Appraisal of techniques and derivation procedures

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Abstract

Recent developments in laboratory techniques adopting highly precise local instrumentation have made possible the determination of all five independent elastic parameters necessary for describing the small-strain stiffness in cross-anisotropic soils. However, the techniques and the derivation procedures are not necessarily straightforward, and different processes sometimes lead to apparently inconsistent sets of parameters, revealing their complex and sensitive nature. This paper firstly reports a new fully-instrumented triaxial system that was optimised to test Japanese standard-sized (∅70–75 mm) clay samples. The testing techniques and procedures to obtain the five cross-anisotropic elastic parameters, defined in this paper for recoverable strain smaller than 0.001%, are reviewed. Some updates, including notes on how to deal with creep in soft clays and the optimisation of drained probe rates, are described. A simplified procedure is proposed for completing the parameter determination, without actually measuring the radial displacement, by inverting the relationship between the undrained Young's modulus and the drained elastic parameters in saturated soils. The validity of this approach is demonstrated by comparing the parameters of sedimentary clays obtained with and without radial measurements. By eliminating the need for complex radial instrumentation, this approach will make the quantification of stiffness anisotropy more accessible in less-equipped laboratories.

Keywords: Anisotropy; Elastic modulus; Small-strain stiffness; Clay

1. Introduction

Sedimentary soils, having been deposited slowly under gravity, normally possess a cross-anisotropic nature, characterised by a vertical axis of symmetry in their mechanical properties. Although subsequent geological processes, such as diagenesis and tectonics, may disturb the symmetry, some studies have demonstrated that initial cross-anisotropic structures are dominant in stiffness of over-consolidated clays and fairly robust against straining, while subjecting the clays to normal consolidation or large-scale shear may eventually alter the anisotropy (e.g., Jovičić and Coop, 1998; Kawaguchi et al., 2008; Cho et al., 2011). It is now clear from studies in the 80s and 90s that soil behaviour at small strains is broadly linear elastic and time-independent (e.g., Tatsuoka and Shibuya, 1991; Jardine, 1992; Tatsuoka et al., 1997). Although the exact strain 'threshold' value, below which soils behave truly elastically, is still being debated, elasticity is at least considered to be a close approximation for the behaviour at strains smaller than

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0.001% for uncemented soils (Tatsuoka and Shibuya, 1991; Jardine, 1992). The engineering significance of the stiffness anisotropy is often invoked in predicting ground deformation induced by tunnel excavations (Lee and Rowe, 1989; Simpson et al., 1996; Addenbrooke et al., 1997; Wongsaroj et al., 2007), but relevant to any two- or three-dimensional problems.

To account for stiffness anisotropy, Graham and Houlsby (1983) introduced a 'three-modulus' cross-anisotropy model, although their original focus was on much larger strains than discussed above. Lings et al. (2000) and Lings (2001) presented a comprehensive review of the cross-anisotropy formulations in soil mechanics and proposed an experimental method combining a set of static small-strain probe loadings and shear wave velocity measurements in a triaxial cell to determine all five independent elastic parameters in the 'full' cross-anisotropy formulation. The same technique was adopted around the same time by Kuwano et al. (2000) and Kuwano and Jardine (2002) for sand, later by Gasparre et al. (2007) for London Clay, and Brosse et al. (2011) and Hosseini Kamal (2012) for several types of mudrock.

A different approach using a calibration chamber fitted with geophysical probes to measure P and S waves was taken by Bellotti et al. (1996) to test dry sand. This method, employing a dynamic method in compressibility measurements, is applicable only to coarse-grained dry soils, in which the compressive behaviour may be insensitive to the drainage conditions of pore fluids.

Another approach is to use a hollow cylinder apparatus (HCA) with independent control of the inner and outer cell pressures (e.g., Minh et al., 2011). By virtue of the ability to control four stress components independently, it allows the determination of the elastic parameters without assuming compatibility between the static and dynamic measurements. This method was adopted by Zdravković (1996) for silt, HongNam and Koseki (2005) and Blanc et al. (2011) for sands, and Minh (2006) and Minh et al. (2011) for London Clay.

The most limiting disadvantage in using an HCA in practice, in addition to its very complex operation and costly instrumentation, is its required specimen size. The above studies on London Clay used specimens 100 mm in outer diameter; those reported in the other studies were 200 mm or greater. The standard pushed tube samplers or rotary core samplers in Japan retrieve samples with diameters of 70–75 mm, and testing them in a fully-instrumented HCA is difficult with the current instrumentation technologies. For this reason, the present study adopts the static-dynamic hybrid triaxial apparatus and optimises the system for specimens 70–75 mm in diameter. According to the author's personal experience, one of the difficulties of this approach is the reliable measurement of radial displacements. This paper firstly reports the carefully designed apparatus and the techniques applied to obtain parameter datasets of the best quality. Using the results as reference, the latter part of the paper assesses the validity of the newly proposed procedures that go way around the problem of radial measurements by conducting undrained probe loading in addition to drained probe loading and then by indirectly deriving all the elastic parameters. The validity of the approach will be further assessed against tests on a horizontally cut specimen, with which the horizontal Young's modulus is more directly measurable.

2. Brief review of elastic modulus derivation from triaxial tests

The theory of cross-anisotropy has been formalised by Love (1927), Pickering (1970), and Raymond (1970), among others, and a thorough review was provided by Lings et al. (2000) and Lings (2001). The cross-anisotropically elastic constitutive equation is

$$\begin{Bmatrix} \delta\varepsilon_x \\ \delta\varepsilon_y \\ \delta\varepsilon_z \\ \delta\gamma_{xy} \\ \delta\gamma_{yz} \\ \delta\gamma_{zx} \end{Bmatrix} = \begin{bmatrix} 1/E'_h & -\nu'_{hh}/E'_h & -\nu'_{vh}/E'_v & 0 & 0 & 0 \\ -\nu'_{hh}/E'_h & 1/E'_h & -\nu'_{vh}/E'_v & 0 & 0 & 0 \\ -\nu'_{hv}/E'_h & -\nu'_{hv}/E'_h & 1/E'_v & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{hh} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{hv} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{vh} \end{bmatrix} \begin{Bmatrix} \delta\sigma'_x \\ \delta\sigma'_y \\ \delta\sigma'_z \\ \delta\tau_{xy} \\ \delta\tau_{yz} \\ \delta\tau_{zx} \end{Bmatrix} \quad (1)$$

where the prime indicates that the parameters are obtained under drained conditions, and hence, defined in terms of the effective stress. Among the eight parameters shown, five of them are independent after considering the following three relationships:

$$G_{vh} = G_{hv} \quad (2)$$

$$\frac{\nu'_{vh}}{E'_v} = \frac{\nu'_{hv}}{E'_h} \quad (3)$$

$$G_{hh} = \frac{E'_h}{2(1+\nu'_{hh})} \quad (4)$$

There are theoretical bounds to the values which these parameters can take (Raymond, 1970; Pickering, 1970; Lings, 2001), but they are not discussed here in detail, as they are seldom violated.

2.1. Conventional procedures with full instrumentation

The subscripts in Eq. (1) are redefined to consider triaxial tests, with z replaced by v (vertical = axial) and x and y replaced by h (horizontal = radial). By conducting an 'axial probe loading', in which σ'_v is changed by a small amount