Engineering Geology 152 (2013) 122–132

Contents lists available at SciVerse ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Yield stress history evaluated from paired in-situ shear moduli of different modes

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ARTICLE INFO

Article history:
Received 19 June 2012
Accepted 4 November 2012
Available online 12 November 2012

Keywords:
Anisotropy
Consolidation tests
In-situ tests
Shear modulus
Shear wave velocity
Stress history

ABSTRACT

A special compiled database of shear moduli from different directional and polarization modes (HH, HV, and VH waves) at well-documented geologic sites shows that stiffness ratio ($G_{0,HH}/G_{0,VH}$) can be used to assess the yield stress ratio (YSR) in soils. In general, the reference profiles of YSR for these sites were determined using series of laboratory consolidation tests on undisturbed samples at varied elevations, coupled with a good understanding of the engineering geology background of the formations. For stress history assessment in soils, various empirical correlations were derived from multiple regression analyses using the stiffness ratio and additional variables.

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1. Introduction

The stress history of soils is a primary characteristic that relates to many fundamental aspects of soil behavior and results from the complete geological evolution over time and various environmental factors. Considering the soil as an approximate elasto-plastic particulate media, the yield stress (σ_y') represents an important break point that separates elastic and plastic response regions. In conventional geotechnical terms, the preconsolidation stress (σ_p' or P_c') which indicates a past maximum vertical overburden stress, has been considered an equivalent parameter. However, the magnitude of σ_p' is commonly used to concern the increase of stress due to mechanical geologic experiences. For instance, Burland (1990) described the yield point at which a notable volumetric reduction occurs during aging process of reconstituted samples as 'quasi-preconsolidation pressure'. It corresponds to the term σ_y' distinguished from σ_p'. The yield stress σ_y' is a more accurate and comprehensive term which includes post-depositional processes such as aging, weathering, cementation, and diagenesis of sediments (Gasparre, 2005; Boone, 2010). The overconsolidation ratio (OCR) is a well-known and classic normalized parameter based on the σ_p' and effective vertical stress (σ_{vo}') such that: $OCR = \sigma_p'/\sigma_{vo}'$. Similarly, yield stress ratio (YSR) can be defined as the magnitude of the σ_y' normalized by σ_{vo}'. In this study, the more complete terms yield stress (σ_y') and YSR are used to represent the stress history of natural soil deposits (Jardine et al., 2004).

Several overconsolidation mechanisms for natural soils have been explained in prior studies (Skempton, 1961; Parry, 1970; Bjerrum, 1972; Mesri and Choi, 1979; Jamiolkowski et al., 1985; Chen and Mayne, 1994). The most common is mechanical loading–unloading that occurs from erosion, past glaciations, and excavation or removal of prior structures. Another important cause is increase of porewater pressure influenced by fluctuations of groundwater table, artesian water, and/or desiccation by capillary effect. As noted in the yield stress definition, the alteration of soil structure (e.g., aging, weathering, cementation) can affect the apparent overconsolidation of natural soil deposits as well. In the field, the estimated YSR profiles tend to be quite different for each mechanism, furthermore the genuine stress history might be rather complicated due to combined complex mechanisms (Chen and Mayne, 1994).

2. Background: yield stress evaluation

A basic and conventional method to determine the yield stress is a laboratory one-dimensional consolidation test using an oedometer or consolidometer (e.g., ASTM D2435) or constant-rate-of-strain device (ASTM D4186). On the basis of this test, a number of interpretative approaches have been developed for delineation of the yield stress. Table 1 summarizes a number of various methodologies (modified after Arnal, 2009). While consolidation testing is expected to provide a reliable yield stress of the in-situ condition, there can be uncertainties and variances between the σ_y' evaluation methods because they are determined based on empirical and graphical observations (Boone, 2010). Moreover, the shape of the consolidation curve (e.g., e–logσ_v' plot) tends to be changed or shifted by influences of sample disturbance effect, load incremental ratio ($LIR = \Delta\sigma/\sigma_{initial}$) effect, specimen thickness, swelling, friction, and other variables (Van Zelst, 1948; Wahls, 1962; Ladd, 1991).

Although the laboratory consolidation test is the primary method to define σ_y', it is relatively expensive, provides only a single point,

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0013-7952/$ – see front matter. Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.enggeo.2012.11.001

Table 1
Summary of σ_y' evaluation methods (modified after Arnal, 2009).

Reference	Method type
Casagrande, 1936	e–logσ_v' plot, graphically constructed
Van Zelst, 1948	e–logσ_v' plot, Rebound method
Burmister, 1951	e–logσ_v' plot
Schmertmann, 1955	e–logσ_v' plot, graphically constructed
Janbu, 1969	Stress–strain and modulus–strain
Jamiolkowski and Marchetti, 1969	1/m_v–logσ_v' plot, graphically constructed
Pacheco Silva, 1970	e–logσ_v' plot, graphically constructed
Sällfors, 1975	e–logσ_v' plot, organic soils
Andersen et al., 1979	Back calculated from S_u
Butterfield, 1979	ln(1 + e)–logσ_v' plot
Graham et al., 1981*	Curve-fitting of experimental data
Oikawa, 1987	log(1 + e)–logσ_v' plot
Becker et al., 1987	W–σ_v' Work-Energy method
Tavenas et al., 1987	e–logσ_v' plot
Jose et al., 1989	log(e)–logσ_v' plot
Hardin, 1989	1/e–$(\sigma_v'/\sigma_{atm})^p$ plot
Burland, 1990	I_{vo}–logσ_v' plot
Jacobsen, 1992	Empirical estimation or graphically constructed
Dias and Pierce, 1995	Spreadsheet procedure using a combination of methods
Onitsuka et al., 1995	ln(1 + e)–logσ_v' plot
Chetia and Bora, 1998	Empirical expression based on OCR and e_L
DeGroot et al., 1999*	Relationship between σ_y', S_u, and index properties
Senol and Saglamer, 2002	Strain–stress plot
Wang and Frost, 2004	Energy–p space, Dissipated Strain Energy Method
Clementino, 2005*	e–logσ_v' plot, graphically constructed
Solanki and Desai, 2008	Empirical correlations (e/e_L)
Mesri and Vardhanabhuti, 2009	e–logσ_v' plot, granular soils
Boone, 2010*	e–logσ_v' plot, simple slope-intercept mathematics

Note: references with * symbol are added after summary collection by Arnal (2009); e = void ratio, 1/m_v = constrained modulus, W = work per unit volume, I_{vo} = void index, s_u = undrained shear strength, e_L = void ratio corresponding to liquid limit.

and takes 2 to 3 days time (automated consolidometer) and up to 2 weeks for manually-operated oedometer. Moreover, the consolidation test is rather problematic for silts and sands since undisturbed samples are very difficult and very expensive to procure, as well as the resulting e–logσ_v' curves are too flat to select a yield point. Therefore, methods for evaluating stress history from in-situ test data have been proposed, such as the cone penetration test (CPT), flat dilatometer test (DMT), standard penetration test (SPT), and vane shear test (VST). Conceptually, it is possible to relate in-situ penetration data (e.g., q_t, p_0, N_{60}, s_{uv}) with the effective yield stress and yield surface (Mayne, 2007). Each in-situ test has a unique stress path (Mayne, 2005). Two examples of the empirical correlations via field tests are provided in Fig. 1. These include following evaluations: (1a) σ_y' from CPT net cone resistance ($q_t - \sigma_{vo}'$) in various soil types (Mayne et al., 2009), (1b) σ_y' from $S_{u,VST}$ and I_P in clays (Leroueil and Jamiolkowski, 1991). In spite of the noted uncertainty and scatter in these data, the utilization of in-situ test data is an attractive and efficient means for profiling the yield stress because of multi-fold reasons: (1) immediate results are available, (b) continuous readings are obtained with depth, and (c) data are collected quickly and economically. Furthermore, they can be used to corroborate the lab results as well as fill-in data between the discrete sampling elevations.

3. Shear stiffness and stress history relationship

The small-strain shear modulus (G_0 or G_{max}) is a fundamental stiffness which is the beginning of all stress–strain–strength curves in soils (Fahey, 1998; Mayne et al., 2009). In laboratory scale, G_0 is often obtained from resonant column (RC) tests and/or bender element (BE) tests. The BE test can provide the G_0 in different planes because it generates multiple types of shear waves. The value of G_0 is directly calculated from the total soil mass density (ρ_T) and shear wave velocity (V_s) as follows:

$$G_{0,ij} = \rho_T \cdot V_{s,ij}^2 \tag{1}$$

where 'i' is propagation direction and 'j' is polarization direction of shear wave. Suppose the plane directions (i–j) are parallel to vertical and horizontal major axis, mainly three different planes can be defined (i.e., $G_{0,VH}$, $G_{0,HV}$, $G_{0,HH}$ or V_{sVH}, V_{sHV}, V_{sHH} — the subscript 'V' is for vertical and 'H' is for horizontal). In field testing, the types of shear wave mode can be generated in boreholes using downhole tests (DHT) and crosshole tests (CHT). For example, the borehole DHT using a horizontal surface source provides the common V_{sVH} mode (Hoar and Stokoe, 1978). Similarly, the direct-push versions of DHT which include the seismic piezocone test (SCPTu) and seismic dilatometer test (SDMT) also produce V_{sVH}. The V_{sHV} type is obtained from standard CHT array using a downhole vertical up–down hammer source (Hoar and Stokoe, 1978). For the V_{sHH} type, a special version of CHT having a horizontal source-generating system is used, including: rotary hammer (Butcher and Powell, 1996); special vane source (Sully and Campanella, 1995); or encased horizontal solenoid (Hiltunen et al., 2003) These in-situ geophysical methods and different V_s modes are depicted in Fig. 2. It is also possible to produce a set of P- and S-wave using a special suspension logger (Nigbor and Imai, 1994), however this device is not typically used in geotechnical studies but for geologic petroleum-based investigations that are quite deep (20 m < z < 1000 m).

The shear modulus of soils at small strains (i.e., shear strain $\gamma_s < 10^{-4}$) has been studied over the past half-century to understand the influence of various factors including stress level, soil type, void ratio, strain rate, and other variables (Hardin and Richart, 1963; Hardin and Black, 1968; Hryciw and Thomann, 1993; Jamiolkowski et al., 1995; Viggiani and Atkinson, 1995; Pennington et al., 1997; Clayton, 2011). The equations for the initial shear stiffness have led to a general expression as follows (Hardin and Blandford, 1989):

$$G_{0,ij} = S_{ij} \cdot F(e) \cdot YSR^k \cdot P_a^{1-ni-nj} \cdot (\sigma_i')^{ni} \cdot \left(\sigma_j'\right)^{nj} \tag{2}$$

where, $G_{0,ij}$ = elastic shear modulus in the i–j plane, F(e) = void ratio function, P_a = reference pressure, σ_i' = effective stress in the wave propagation direction, σ_j' = effective stress in the wave polarization direction, and S_{ij}, k, ni, nj = empirical material constants. There are three main variables: F(e), YSR, and current effective stress state (σ_i' and σ_j'). For fine-grained soils, it was noted that the initial stiffness is strongly related to two variables such as the confining stress state and either void ratio or YSR (Viggiani and Atkinson, 1995; Rampello et al., 1997; Santagata et al., 2005). In terms of the G_0 variation, the void ratio is a dominating factor in normally consolidated (NC) soils whereas the YSR can more appropriately explain the variation in overconsolidated (OC) soils. Particularly, Choo et al (2011) examined the effect of directional stress history on anisotropy of initial stiffness and suggested the YSR should be included in the empirical G_0 relationship to properly describe the G_0 for OC soils. On the basis of examinations on G_0 data ($G_{0,VH}$ and $G_{0,HH}$) obtained from different planes (e.g., VH — vertical plane, HH — horizontal plane), it was also proposed that directional YSR seems more suitable for the correlation. Similarly, for cohesionless soils, Hryciw and Thomann (1993) developed a stress-history-based model for G_0. The model was expressed based on directional stress history (i.e., YSR for vertical and horizontal directions). Consequently, the initial shear stiffness is strongly related to the stress history albeit the correlations might depend on soil types and site-specific conditions.

The lateral stress coefficient (K_0) is related to stress history and frictional characteristics. Mayne and Kulhawy (1982) proposed the following simple expression for one-dimensional mechanical loading-unloading of soils:

$$K_{0,OC} = (1 - \sin\varphi') \cdot YSR^{\sin\varphi'} \tag{3}$$