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Assessment of clay stiffness and strength parameters using index properties

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A B S T R A C T

A new approach is developed to determine the shear wave velocity in saturated soft to firm clays using measurements of the liquid limit, plastic limit, and natural water content with depth. The shear wave velocity is assessed using the site-specific variation of the natural water content with the effective mean stress. Subsequently, an iterative process is envisaged to obtain the clay stiffness and strength parameters. The at-rest earth pressure coefficient, as well as bearing capacity factor and rigidity index related to the cone penetration test, is also acquired from the analyses. Comparisons are presented between the measured clay parameters and the results of corresponding analyses in five different case studies. It is demonstrated that the presented approach can provide acceptable estimates of saturated clay stiffness and strength parameters. One of the main privileges of the presented methodology is the site-specific procedure developed based on the relationships between clay strength and stiffness parameters, rather than adopting direct correlations. Despite of the utilized iterative processes, the presented approach can be easily implemented using a simple spreadsheet, benefiting both geotechnical researchers and practitioners.

1. Introduction

Determination of the parameters of compressibility and strength of geomaterials is a difficult yet essential task in geotechnical analyses. Reliable estimates of these parameters allow geotechnical engineers to design structures, roads and utilities to be safe, serviceable and economic. Commonly, geotechnical engineers, in the initial phases of the geotechnical investigation, focus on the index properties such as the liquid limit, *LL*, plastic limit, *PL*, natural water content, w_n, and gradation tests. These tests are generally cheap, as they do not require expensive capacious equipment or special experience. They are mainly used to serve in the classification of soils.

The variation of the natural void ratio, e_0, due to changes in the in situ effective vertical stress, σ'_{v0}, may be assessed using measurements of the natural water content, w_n, with depth since w_n and e_0 are interrelated (i.e. $e_0 = G_S w_n/100$ in saturated soils, where G_S is the soil specific gravity). The inferred w_n-σ'_{v0} data can be considered as the result of a natural full-scale sustained oedometer test that cannot be fully replicated in the laboratory even with the use of the most sophisticated equipment and sampling procedures due to the inevitable sample disturbances. Subsequently, distinct clay units (i.e. clay units having different geotechnical characteristics) may be delineated by considering the disclosed w_n-σ'_{v0} relationship as well as values of the *LL* and *PL* pertaining to a specific study area. This simple approach was utilized to characterize the gravitational compression of different natural clays (Skempton, 1970). It is also employed to differentiate between the subunits of London clays (Hight et al., 2007).

Geotechnical engineers commonly utilize clay index properties to estimate the geotechnical parameters. For example, the use of plasticity index, *PI*, to estimate the effective friction angle, ϕ', and the use of the liquidity index, *LI*, to determine the undrained shear strength, s_u, are the normal geotechnical practices. Nevertheless, such correlations have a substantial scatter (Kulhawy and Mayne, 1990; Ameratunga et al., 2015). Fig. 1 shows the obviously scattered *PI*-ϕ' data, pertaining to different clays (Tanaka, 2002), versus a recent *PI*-ϕ' correlation proposed by Sorensen and Okkels (2013). This figure also illustrates that some clays may have a high effective friction angle, ϕ', despite of high plasticity index, *PI*, which contradicts with the commonly related correlations.

Moreover, some clays naturally exist with a liquidity index, *LI*, greater than 100% (i.e. the natural water content, w_n, is greater than the liquid limit, *LL*); yet they have non-trivial undrained shear

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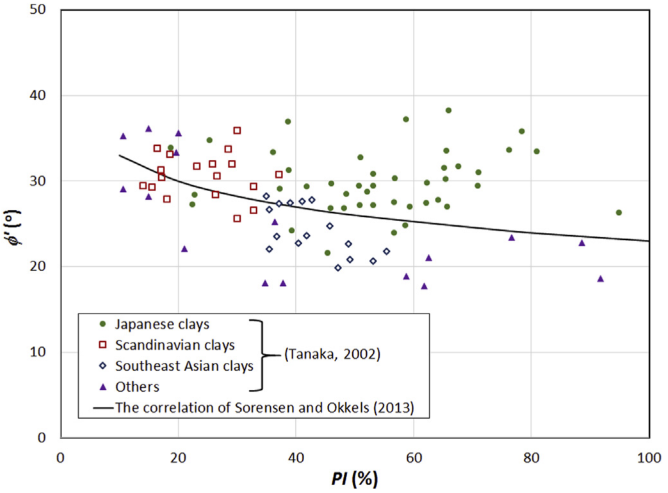

Fig. 1. Relationship between the effective friction angle ϕ' and plasticity index *PI*.

strength, s_u, that increases with depth. This contradicts with the common correlations that relate s_u to *LI* as they presume such clays to have negligible undrained strength. Examples of these clays include Ariake clay in Japan and Champlain clay in Canada (Rochelle et al., 1974; Tanaka et al., 2001).

The above-mentioned discrepancies shed doubts on the reliability of the correlations relating the clay parameters to the index properties. One of the anticipated reasons for these discrepancies is that such correlations are developed based on the data pertaining to particular sites. Hence, inaccuracies may occur when such correlations are applied to other sites with varied clay mineralogy, gradation and/or state of stresses. Additionally, many influencing factors, such as aging, cementation, and anisotropy, cannot simply be incorporated into the correlations that relate clay parameters to the index properties. In this context, site-specific correlations are generally expected to perform better than generic correlations.

In this study, the parameters controlling the site-specific relationships between the shear wave velocity, V_S, the void ratio, e_0, and the effective mean stress, p', are obtained using measurements of the clay index properties with depth. Subsequently, the strength and stiffness parameters are determined using relationships interrelating clay stiffness and strength. The presented approach comprises an iterative site-specific methodology rather than a direct correlation. It can be implemented using a simple spreadsheet. Thus, it can be utilized in both geotechnical research and routine engineering practices.

2. Previous related correlations

The following correlations are utilized in this study as a part of the presented procedures:

(1) The compression index, C_C, is related to the plasticity index, *PI*, as follows (Wroth and Wood, 1978):

$$C_C = G_S\, PI/200 \tag{1}$$

(2) The effective pre-consolidation pressure, σ'_p, is related to the liquid limit, *LL*, plastic limit, *PL*, natural water content, w_n, and effective vertical stress, σ'_{v0}, as follows (Kootahi and Mayne, 2016):

(i) If $DS > 1.123$, then we have

$$\sigma'_p \big/ p_a = 1.62(\sigma'_{v0}/p_a)^{0.89}(LL)^{0.12}w_n^{-0.14} \tag{2}$$

(ii) If $DS \le 1.123$, then we have

$$\sigma'_p \big/ p_a = 7.94(\sigma'_{v0}/p_a)^{0.71}(LL)^{0.53}w_n^{-0.714} \tag{3}$$

where *DS* is the sample discrimination function given as follows:

$$DS = 5.152\log_{10}(\sigma'_{v0}/p_a) - 0.061\,LL - 0.093\,PL + 0.0622\,G_S w_n \tag{4}$$

Subsequently, the overconsolidation ratio, *OCR*, is estimated as follows:

$$OCR = \sigma'_p \big/ \sigma'_{v0} \tag{5}$$

(3) Based on the estimated *OCR*, the at-rest earth pressure coefficient, K_0, can be determined as follows (Mayne and Kulhawy, 1982):

$$K_0 = \sigma'_{h0}/\sigma'_{v0} = (1-\sin\phi')OCR^{\sin\phi'} \tag{6}$$

Accordingly, the mean effective stress, p', can also be determined as follows:

$$p' = \sigma'_{v0}(1+2\,K_0)/3 \tag{7}$$

Eqs. (1)–(7) can simply be substituted with alternative site-specific correlations or factual data without affecting the structure of the presented methodology.

3. Site-specific formulation of the shear wave velocity

Recently, the use of shear wave velocity (either independently or with other parameters) has become an increasing trend in geotechnical engineering. The shear wave velocity has been related to many important geotechnical parameters such as the bulk unit weight, effective friction angle, undrained shear strength, and at-rest earth pressure coefficient (Mayne, 2014; Hussien and Karray, 2016; L'Heureux and Long, 2016; Moon and Ku, 2016a). Moreover, the indispensable need to consider the small-strain stiffness in geotechnical applications is related to the shear wave velocity, which has been frequently demonstrated (Burland, 1989; Atkinson, 2000; Elhakim, 2005; Benz, 2007; Clayton, 2011).

Many studies have shown that the shear wave velocity can be expressed directly as a function of the effective mean stress, p', the soil void ratio, e_0, and the *OCR* (Hardin and Richart, 1963; Hardin, 1978). More recently, a different approach has been presented. The shear wave velocity is expressed as a function of certain site-specific parameters with either the effective mean stress, p', or the void ratio, e_0 (Santamarina et al., 2001; Ku et al., 2016) as follows:

$$V_{S,p'} = \alpha(p'/1\text{ kPa})^{\beta} \tag{8}$$

$$V_{S,e_0} = ae_0^b \tag{9}$$

where $V_{S,p'}$ and V_{S,e_0} are the estimates of shear wave velocity using the mean effective stress, p', or the void ratio, e_0, respectively. The parameters α, β, a, and b are the site-specific parameters.

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