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Evaluation of overconsolidation ratios from laboratory and in situ tests on Busan clay

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ABSTRACT

The overconsolidation ratio (OCR) was determined through three different series of consolidation tests on the samples, which were retrieved using an oil-operated fixed-piston sampler at two sites in a deltaic deposit. The constant rate of strain (CRS) consolidation test and the end-of-primary (IL_{EOP}) consolidation tests proved to be superior tests with higher quality of samples and produced close OCR values. The CRS and IL_{EOP} tests provided OCR values close to those of the field measurements, whereas the conventional 1D consolidation (IL_{24}) test underestimates the values. The OCR values obtained from the CRS and IL_{EOP} tests lie between the upper and lower bounds of existing empirical formulas, whereas those from the IL_{24} test belong to the lower bound. Empirical formulas that were suited for both sites were newly developed through the correlations between the results of the two consolidation tests and three field tests. The empirical formulas, which have been developed based on the correlation coefficients, are appropriate for predicting the OCR values for a site where the great majority of data are given. This trend is more pronounced in the predictions obtained from the piezocone and the field vane tests than the predictions from the flat dilatometer test.

1. Introduction

The overconsolidation ratio (OCR) is defined as the ratio of the "apparent" preconsolidation stress σ'_p to the effective overburden stress σ'_{v0}. σ'_p is related to the stress history, time, and chemical bonding (cementation) of soil deposits, which significantly affects the geotechnical behavior of natural deposits (Burland, 1990; Nagaraj and Miura, 2001). The OCR is evaluated using the σ'_p values obtained from 1D consolidation tests. However, σ'_p varies depending on various consolidation test methods. Examples are the standard 1D consolidation tests (ASTM D 2435-04, 2007) with a constant load increment duration of 24 h (IL_{24}) and a successive load increments applied after 100% primary consolidation (end-of-primary consolidation, IL_{EOP}); and a constant rate of strain (CRS) consolidation test (ASTM D 4186-06, 2007). Graphical construction methods of determining σ'_p (Burmister, 1952; Brumund et al., 1976; Casagrande, 1936; Janbu, 1963, 1998; Schmertmann, 1955; Silva, 1970) and the applied strain rate for the CRS test (Leroueil et al., 1985; Ozer et al., 2012) also affect σ'_p. Moreover, the disturbance of the samples used for the consolidation tests is a crucial factor. Thus, the values of σ'_p that are obtained from laboratory consolidation tests should be comparable to those obtained from field measurement (Leroueil et al., 1978, 1983; Morin et al., 1983).

Many empirical methods that determine σ'_p (or OCR) are based on various in situ tests, which can avoid the effects of the aforementioned disadvantageous factors. In particular, the in situ tests are insignificantly affected by sample disturbance and testing methods. In addition, the in situ tests are cheaper and faster than laboratory tests. However, the laboratory consolidation test result, as the reference value, significantly affects the developed empirical methods. For this reason, developing any empirical formulas with data that have no information regarding the applied sampling techniques and consolidation test methods would be meaningless. The applicability of the empirical formulas developed using the experimental data at several sites to any types of clay in the world is also doubtful. Thus, high-quality sampling technique and a consolidation test method that produces OCR or σ'_p values nearly identical to those from the field measurement at a site should be used to clarify the uncertainty of the empirical formulas.

This study aims to develop empirical methods that determine the OCR of Busan clay by using different in situ tests. An oil-operated fixed-piston sampler (Chung and Kweon, 2013), which is known as one of the best fixed-piston samplers, was applied at two sites of Nakdong River Delta in Busan City, Korea. Three main in situ tests, including field vane test (FVT), piezocone (CPTu), and flat dilatometer (DMT), were conducted. Various consolidation tests were also conducted to investigate the effect of the referred OCR values. On the basis of the proper consolidation test and in situ test results, empirical formulas that are suited for both sites are proposed. The OCR values estimated using the proposed empirical methods are also compared with those from existing empirical methods. The applicability of the empirical methods to Busan clay is then discussed.

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2. Methods for determining OCR

2.1. Field measurement

The in situ preconsolidation stress can be determined through field measurements (Leroueil et al., 1978, 1983; Morin et al., 1983). Morin et al. (1983) suggested five methods for determining the in situ σ'_p by using the field records of settlements and/or pore pressure as well as the behavior of the sensitive clays monitored during and after surface load placement. They reported that the in situ σ'_p values obtained through the stress–strain relationship, water content, and pore pressure generation during construction produced good correlations with those from the conventional laboratory σ'_p. The σ'_p obtained using the monitored settlement underestimates or overestimates the laboratory values. Leroueil et al. (1978) reported that the laboratory σ'_p values were smaller than the in situ σ'_p values for normally consolidated clays, equal to those for slightly overconsolidated clays ($OCR < 2.5$), and higher than those for heavily overconsolidated clays.

2.2. Consolidation tests in the laboratory

The σ'_p values determined using various 1D consolidation test methods are different. In addition, the sample quality, specimen size, loading duration, and strain rate affect the laboratory σ'_p values. For example, Leroueil et al. (1983) reported that the IL_{24} test with a load increment ratio of 0.5 produced the σ'_p values that are comparable to the field values; however, Jamiolkowski et al. (1985) recommended the IL_{EOP} test. Meanwhile, Chung et al. (2014a) suggested a modified end-of-primary consolidation test (ILM_{EOP}), in which one or more additional loading steps were applied between the stress increments spanning the possible value of σ'_p during the IL_{EOP} test.

Furthermore, σ'_p can be determined from the compression and tangent modulus curves through several graphical construction methods (Ku and Mayne, 2013). The σ'_p values obtained using Casagrande graphical method depend on the graph scale and individuals. By contrast, the methods of Silva (1970) and Janbu (1963, 1998) can determine a σ'_p value that is independent of individuals (Fig. 1). In fact, sample disturbances and consolidation testing methods would affect the values of σ'_p more significantly than graphical methods.

2.3. Empirical methods based on field soil tests

Many empirical methods for determining σ'_p based on the FVT, CPTu, and DMT have been proposed. The methods used in this study are summarized in Table 1 [Eqs. (1)–(9)]. The FVT-based empirical equations (Eqs. (1)–(3)) have been essentially developed based on Eq. (10).

$$(s_{u,OC}/\sigma'_v) = (s_{u,NC}/\sigma'_v)(OCR)^m \tag{10}$$

where $(s_{u,OC}/\sigma'_v)$ is the normalized undrained shear strength of overconsolidated clay and replaced with the normalized field vane strength [i.e., $(s_{u,FV}/\sigma'_v)$ in Eq. (1)], $(s_{u,NC}/\sigma'_v)$ is the normalized undrained shear strength of normally consolidated clay, and m is a constant that is related to the plastic volumetric strain and varies according to undrained strength test types. Similarly, $(s_{u,NC}/\sigma'_v)$ in Eqs. (2) and (3) was expressed in different forms.

The CPTu-based empirical formulas were suggested based on the net cone resistance $(q_t - \sigma_v)$, effective cone resistance $(q_t - u_2)$, pore pressure parameter B_q, shear modulus G_0, and effective overburden stress σ'_{v0}. Eqs. (4)–(8) were proposed for various types of clays.

Many DMT-based empirical methods are available. All the equations are related to the horizontal stress index (K_D) with different values of constants λ and n. Marchetti (1980) suggested that $\lambda = 0.34$ and $n = 1.56$ for uncemented cohesive clays ($0.2 < I_D < 2$), where I_D is the material index. However, $\lambda = 0.13$–2.7 and $n = 0.75$–1.67 for various types of clays (Table 1).

3. Test program

3.1. Site description

Soil investigation was conducted at two sites in the floodplain, central-west of the Nakdong deltaic plain. The soil profile comprised a silty sand layer at the first 4 m from the ground surface, followed by a thick, soft, and compressible silty clay layer up to 32 m, and the sandy gravel to sand layer on the Cretaceous basement rock. The sea level changes during the Late Quaternary formed the deposit. On the basis of the depositional environment investigation, the entire deposit in the deltaic plain is commonly divided into four units (Ryu et al., 2005). Unit I consists of fluvial channel (composed of sand and sandy gravel) above the Cretaceous basement rock; Unit II consists of shallow

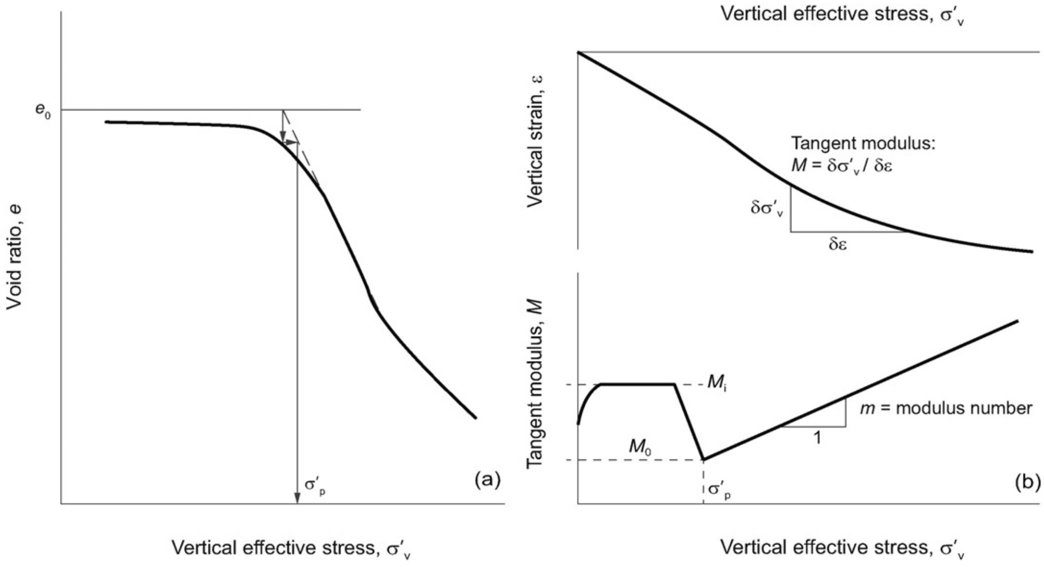

Fig. 1. Determination of preconsolidation stress: (a) Silva's (1970) method; (b) Janbu's (1963, 1998) method.