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Laboratory test and empirical model for shear modulus degradation of soft marine clays

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ABSTRACT

The change in the shear modulus of clays under repeat environmental loads is an important factor in the design of offshore and onshore foundations. A degradation model for the shear modulus of soft clays that considers the effects of the number of cycles, the cyclic stress ratio, the loading frequency and the plasticity index is proposed. A series of undrained cyclic triaxial tests on undisturbed Shanghai marine clays were conducted. Experimental results reveal that the shear modulus degradation index has a logarithmic relationship with the number of cycles, decreases linearly with the cyclic stress ratio, and increases linearly with the loading frequency when plotted in log-log coordinates. Further study using existing data from other research shows that the degradation index decreases with plasticity index, I_P. Based on the test results, a new degradation model is proposed which considers these factors explicitly. The main feature of the new model is that only one set of parameters for each type of clay is required for the prediction of shear modulus degradation. The applicability of the present model is verified by five soft clays with different plasticity indices and loading conditions.

1. Introduction

In recent years, an increasing amount of offshore and coastal infrastructure has been installed in clayey ground in marine environments, and these include pile foundations, spudcans and anchors (Gaudin et al., 2011; Zhu et al., 2012; Elkasabgy and El Naggar, 2013; Bao et al., 2014; Abbasa et al., 2015; Tian and Cassidy, 2011; Tian et al., 2015). These structures are subject to environmental loadings such as wave or wind loadings, and cyclic loading needs to be taken into consideration in the design of their foundations. In addition, earthquakes and traffic loadings (Abu-Farsakh et al., 2015; Ishikawa and Miura, 2015; Shen et al., 2014; Wu et al., 2015b) are other types of cyclic loading for onshore foundations in clayey ground. Transient dynamic loading can also be induced during underground construction activities such as tunnelling (Ye et al., 2015; Han et al., 2016, 2017) and jet-grouting (Shen et al., 2013; Wang et al., 2013). The dynamic response of clay under cyclic loading, especially the degradation of shear strength, is one of the major concerns in the design of foundations for marine and onshore structures.

Many experimental studies have been conducted on the dynamic properties of clays in the last few decades (Sangrey et al., 1978; Procter and Khaffaf, 1984; Ansal and Erken, 1989; Hyde et al., 1993; Matasovic and Vucetic, 1995; Zhou and Gong, 2001; Li et al., 2011; Gu et al., 2012; Patiño et al., 2013; Wang et al., 2013a, 2013b; Wichtmann et al., 2013; Taukoor and Rutherford, 2016; Wijewickreme and Soysa, 2016). The results of these studies indicate that the shear modulus degradation of clays is progressive and that the degree of degradation depends on several factors, which can be classified into two categories: (1) loading conditions, including the cyclic stress level, the loading frequency, and loading directions; and (2) soil characteristics, including overconsolidation ratio, stress status, and Atterberg limits. However, the challenge for engineers is to consider all these factors for the prediction of the cyclic degradation of clays. Based on a database of cyclic triaxial tests on various soils, a cyclic strength diagram was proposed and applied to predict the bearing capacity of foundations (Andersen and Lauritzsen, 1988; Andersen, 2009), in which isolines with the number of cycles to failure, and the deformation failure mode measured for the different average shear stresses and shear stress amplitudes, were presented. From the experimental observations, various models have been proposed.

Two types of model have been commonly used for the prediction of the dynamic behaviour of clays. One is the elastoplastic constitutive model (e.g., Wheeler et al., 2003; Zhang et al., 2007, 2011), which normally employs elements from plasticity theory such as yielding

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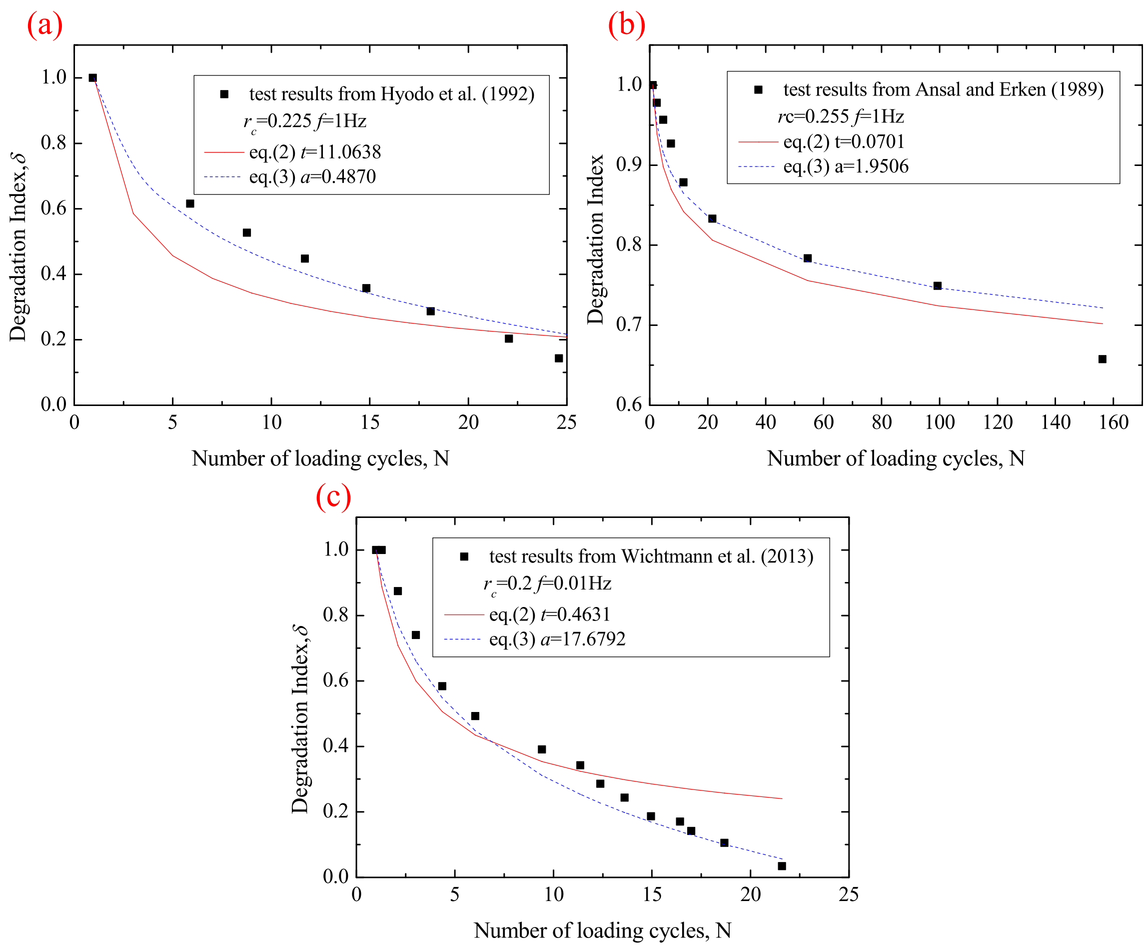

Fig. 1. Comparison between the test results and prediction by Eqs. (2) and (3). (a) Test results of Hyodo et al. (1992). (b) Test results of Ansal and Erken (1989). (c) Test results of Wichtmann et al. (2013).

surfaces and flow rules, to define a stress-strain relationship for soils. This approach can describe the behaviour of clays under various loading conditions and drainage conditions. However, the numerical analysis implemented with the elastoplastic model requires a significant amount of computational resources. Therefore, it is difficult to apply this model to offshore or onshore engineering structures which are subject to a large number of cyclic loads (Gu et al., 2016). The other model is the empirical model (e.g., Idriss et al., 1978; Yasuhara et al., 1998). The empirical model normally provides the cumulative strain or stiffness modulus by an expression of the number of cyclic loads directly. Thus, it is suitable for computations with a large number of cyclic loads, such as those for offshore engineering and highway engineering structures (Chai and Miura, 2002; Shen et al., 2015). However, the empirical model has its limitations and cannot consider complex loading conditions and soil properties. For the purpose of application in engineering numerical analysis, it is necessary and desirable to overcome these limitations of conventional empirical models.

In this study, the influence of cyclic stress ratios, loading frequencies and plasticity index on the strength degradation are investigated in detail using cyclic triaxial tests on undisturbed Shanghai marine clay and four other clays. Based on the test results, a shear modulus degradation model that takes into consideration these factors is proposed.

2. Empirical equations for shear modulus degradation

The degradation of shear strength is a major concerning factor in the dynamic properties of clayey soils. Idriss et al. (1976, 1978) defined a shear modulus degradation index (δ) to evaluate the degree of degradation quantitatively. In stress-controlled triaxial cyclic tests, the shear modulus degradation index δ can be calculated as follows (Idriss et al., 1976):

$$\delta = \frac{G_{SN}}{G_{S1}} = \frac{\frac{\sigma_d}{\varepsilon_{CN}}}{\frac{\sigma_d}{\varepsilon_{C1}}} = \frac{\varepsilon_{C1}}{\varepsilon_{CN}} \tag{1}$$

where σ_d is the cyclic stress amplitude; G_{S1} and G_{SN} are the cyclic shear modulus at cycles 1 and N, respectively; ε_{C1} and ε_{CN} are the cyclic double amplitude strains at cycles 1 and N, respectively. From Eq. (1), it can be seen that the degradation index δ is equal to the ratio between the cyclic axial strain at cycles 1 and N. The degradation index, δ is always less than 1.0, and higher value of δ means a lower degree of degradation.

Several expressions for the degradation index δ have been proposed in the last few decades, which can be divided into two categories.

(1) Equation using exponential relationship

Idriss et al. (1978) found that δ versus N (number of cyclic loading) plotted as a straight line in a log-log scale:

$$\delta = N^{-t} \tag{2}$$

where t is a degradation parameter.

Eq. (2) is so simple that it can be handled easily by geotechnical engineers, although the accuracy of its prediction was not high in some cases, which is demonstrated later. The $\delta \sim N$ relationship that was