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Undrained pore pressure behavior of soft marine clay under long-term low cyclic loads

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ABSTRACT

Long-term low cyclic loads are often encountered in marine environment, but the cyclic behavior of soil under this loading condition is rarely studied. Undrained pore pressure behavior of soft marine clay subjected to long-term low cyclic loading is of considerable importance for the proper design and maintenance planning of foundations of near- and off-shore structures. In this paper, a new hyperbolic model is proposed to predict the development of undrained pore pressure. This model is verified by experimental data from literature. Compared with the existing models, the proposed model has better capability and performance. With use of the proposed model, a hyperbolic relationship between cumulative plastic strain and pore pressure was derived and verified by experimental data. Finally, the effects of cyclic stress ratio, confining pressure and loading frequency on pore pressure are investigated. In summary, this work provides a novel model and some innovative observations to better understanding undrained pore pressure behavior of soft marine clay under long-term low cyclic loads.

1. Introduction

Soft marine clay, widely distributed in the east area of China, is very fragile to be disturbed due to its own physical and mechanical properties (e.g., high sensitivity, high void ratio, low permeability, etc.) (Ren et al., 2018). In this marine environment, many off- and near-shore structures are founded such as suction anchors, seawalls, ports, etc., whose foundations are usually subjected to cyclic loads caused by waves, traffic vehicles and machines. These cyclic loads, usually being of numerous repeated applications and low-stress level, can generate excess pore water pressure. The generated excess pore water pressure probably not result in a failure of soil, but can lead to a deterioration of bearing capacity and soil strength (Ansal and Erken, 1989; Moses et al., 2003; Andersen, 2009; Li et al., 2011; Wichtmann et al., 2013) and to unexpected deformation (Ren et al., 2012; Deng and Ren, 2017; Ng et al., 2013; Lei et al., 2016). Thus, for proper design and maintenance planning of the foundations of near- and off-shore structures, it is essential to investigate the response of pore water pressure of soft marine clay under cyclic loads.

Many researchers have investigated on pore pressure development of soils under cyclic loading (e.g., Lo, 1969a, 1969b; Wilson and Greenwood, 1974; Yasuhara et al., 1982; Hyde and Ward, 1985; Hyodo et al., 1992; Zhou and Gong, 2001; Jeng and Cha, 2003; Moses and Rao, 2007; Wang et al., 2013, 2017; Tang et al., 2015). Some empirical models (Matsui et al., 1980; Yasuhara et al., 1982; Ohara and Matsuda, 1988; Hyde et al., 1993; Xu et al., 1997; Moses et al., 2003; Nie et al., 2007) and theoretical models (Carter et al., 1980; Ramsamooj and Alwash, 1990; Li and Meissner, 2002; Ni et al., 2015) have been proposed to describe the pore water pressure development of clayey soils based on cyclic triaxial tests. Because of the complexity of parameters and computation cost, the theoretical models have not been as widely used as the empirical models in practical engineering. These excellent works provide solid tools for further understanding the cyclic behavior of soils under different loading conditions. However, most of these studies focused on the loading condition only for a small number of cyclic applications (usually smaller than 2000). In the marine or traffic environment, however, the number of loading cycles usually reach hundreds of thousands or even more; meanwhile, its applied cyclic stress level is usually lower than the critical

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cyclic stress of soil. This loading condition is called long-term low cyclic loading herein. Under this condition, pore water pressure behavior of soft clay has been rarely studied before.

In present study, we aim to propose a new empirical model to describe the pore pressure development of soft marine clay under the long-term low cyclic loads. This model particularly focuses on two aspects of loading conditions not considered in previous models, 1) lower stress level that the cyclic stress is lower than the critical cyclic stress (see detailed definition and discussion of critical cyclic stress for different soft soils in Ren et al., 2018) and 2) larger loading cycles. In the following, firstly we briefly review the existing pore pressure models and propose a new model specifically for long-term low cyclic loading condition in section 2. Secondly, verification and application of the new model are made in section 3. Then, the effects of cyclic stress ratio, confining pressure and loading frequency on pore pressure as well as limitations of the current study are discussed in section 4. At last, summary and main conclusions are drawn in the last part of the paper.

2. Pore pressure buildup modeling

2.1. A brief review of pore pressure model

The two most widely used empirical models are briefly introduced in this section. Hyde and Ward (1985) proposed a power model for pore pressure of silty clay under unstrained conditions using monotonic strain-controlled cyclic triaxial tests. A simpler similar power model was put forth by Huang et al. (2000) for Shanghai clay as follows,

$$\frac{u}{p_0} = aN^b \tag{1}$$

where u is the pore pressure; p_0 is the initial mean effective stress, $p_0 = (\sigma'_1 + \sigma'_2 + \sigma'_3)/3$; N is the number of cyclic application; a, b are model parameters and depend on cyclic stress.

Ohara and Matsuda (1988) carried out a series of two-way strain controlled cyclic simple shear tests under the undrained condition for kaolinite clay. They developed a hyperbolic model to describe pore pressure development with respect to the number of cycles. Considering that it is difficult to determine the model parameters by cyclic strain, following Ohara and Matsuda (1988), a similar hyperbolic model was suggested by Paul et al. (2015) wherein model parameters are dependent on stress state (e.g., loading frequency, cyclic stress, confining pressure) and soil properties (e.g., plasticity index I_p). It was expressed as the following equation,

$$\frac{u}{\sigma'_{vc}} = \frac{N}{\alpha + \beta N} \tag{2}$$

where σ'$_{vc}$ is the effective confining pressure; α and β are model parameters, which can be expressed as a function of cyclic stress, effective confining pressure, loading frequency and plasticity index. Some other similar power/hyperbolic models or other type models have been proposed by Hyodo et al. (1988), Matasovic and Vucetic (1995), Nie et al. (2007), Yao et al. (2012).

The above two models were proposed on the basis of experiments conducted under the loading condition of only a few cycles with high cyclic stress level. Under this condition, the excess pore pressure would accumulate and increase steeply, even resulting in a failure of soil within a few cycles. Under long-term lower cyclic stress level, however, the pore pressure will accumulate at a smaller rate, and the increment of pore pressure will decrease over loading cycles. When the increment of pore pressure is small enough and equal to its dissipation over a long time, the generated pore pressure will finally tend to be plateaued without leading to a failure of soil. This has been experimentally confirmed by many researchers (e.g., Ohara and Matsuda, 1988; Zhou and Gong, 2001; Moses and Rao, 2007; Cui et al., 2014).

2.2. A new pore pressure model for long-term low cyclic loading condition

Following the above observations, pore pressure development under the long-term low cyclic loading can not be predicted by the power equation (1) because the pore pressure that this model demonstrates will increase endlessly instead of being plateaued over against the loading cycles N. Although the equation (2) proposed by Paul et al. (2015) is capable of describing the plateaued curve, it will produce large error when used to predict pore pressure generated by long-term low cyclic loading (seen from later section 3.1) because the model is not proposed specifically for this loading condition.

To accurately predict the undrained pore pressure, a new model is proposed specifically for the long-term low cyclic loading condition as follows:

$$\frac{u}{p_0} = \frac{N^B}{A + CN^B} \tag{3}$$

where u is the pore pressure; p_0 is the initial mean effective stress, $p_0 = (\sigma'_1 + \sigma'_2 + \sigma'_3)/3$, and p_0 is equal to σ'_{vc} Eq. (2) when it is in isotropic consolidation; A, B, C are model parameters that depend on stress state and physical properties of soil. When $B = 1$, the Eq. (3) is simplified into Paul's model of Eq. (2).

2.3. Parameters of the proposed equation

As the pore pressure is strain related (Lo, 1969a, 1969b; Hyde et al., 1993; Moses and Rao, 2007; Tang et al., 2015), the factors that control the strain will also be the dominant factors of pore pressure, e.g. cyclic stress, effective confining pressure, soil static strength, etc. The influence of these factors can be captured by the model parameters. To better analyze the physical meaning of the parameters A, B, C in the proposed model, they can be analogized respectively to the parameters a, b, c in Ren's model (Ren et al., 2018) because this two models are consistent in mathematical form. The exponent parameter B represents the slope of pore pressure ratio u/p_0 versus $\log_{10}N$ plot. It characterizes the rate of pore pressure developing, but it does not affect the permanent pore pressure generation. This indicates that the parameter B may only depend on the physical properties of the soil itself, and should be independent of stress state.

To examine whether the parameter B is cyclic stress state dependent or not, we plot the parameter B versus the cyclic stress ratio (CSR) as shown in Fig. 1. The values of the parameter B are obtained by regression method with use of Eq. (3) fitting the compiled experimental data. It can

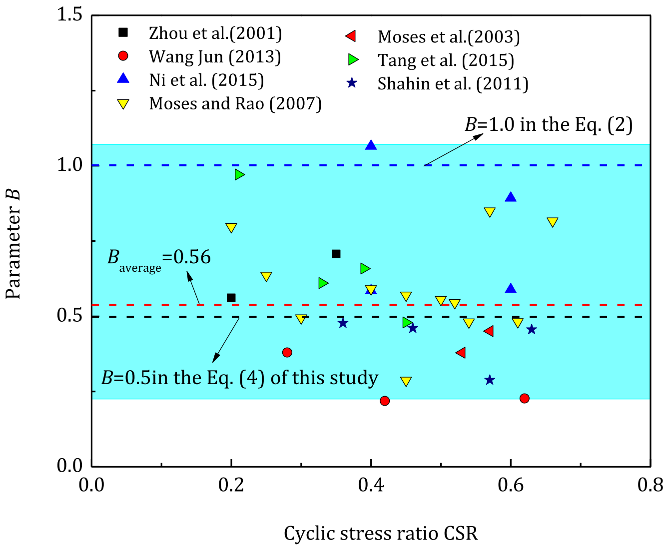

Fig. 1. Effect of the stress state on parameter *B*.