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Deformation characteristics of overconsolidated clay sheared under constant and variable confining pressure

Chuan Gu[a,b], Jun Wang[a,b,*], Yuanqiang Cai[a,b,c], Lei Sun[c], Peng Wang[a,b], QuanYang Dong[a,b]

[a]*College of Civil Engineering and Architecture, Wenzhou University, Wenzhou 325035, PR China*

[b]*The Key Laboratory of Engineering and Technology for Soft Soil Foundation and Tideland Reclamation of Zhejiang Province, Wenzhou University, Wenzhou 325035, PR China*

[c]*Research Center of Coastal and Urban Geotechnical Engineering, Zhejiang University, Hangzhou 310058, PR China*

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Abstract

The traffic-induced settlements of clay subgrade are usually investigated based on one-way cyclic triaxial tests. Most one-way triaxial cyclic tests on clays have been carried out on normally-consolidated samples, with a constant confining pressure and under undrained conditions. However, it has been found that the varying stress field induced by traffic loading consists of not only cyclic axial stresses, but also cyclic horizontal stresses and shear stresses. Sometimes part of the subgrade soil is overconsolidated, rather than normally-consolidated, and the drainage of pore water is usually allowed under long-term traffic loading. Recognizing this, a series of one-way cyclic triaxial tests was performed on 30 specimens under partially-drained conditions, and the emphases were placed on the coupling effects of the overconsolidation ratio, the cyclic stress ratio, and the cyclic confining pressure on the deformation characteristics of the saturated clay. The test results show that increasing the amplitudes of cyclic confining pressure will cause a remarkable acceleration in the accumulation of both the permanent volumetric strain and the axial strain, whether the sample is overconsolidated or normally-consolidated. A linear relationship is found between the permanent axial strains from tests with variable confining pressure and their counterparts obtained from tests with constant confining pressure, regardless of the OCR and CSR values. A quantitative relationship, which considers the effects of the OCR values, is also established between the increments in cyclic confining pressure amplitudes and the increments in permanent axial strain.

Keywords: Cyclic loads; Triaxial tests; Soft clay; Overconsolidation ratio; Soil deformation

1. Introduction

The prediction and control of subgrade settlements are key factors influencing the quality of road construction, especially in areas of soft clay such as eastern coastal China. This is mostly because natural soft clays normally have high water contents, large void ratios, and low shear strength, thus promoting both the uniform and the differential settlements of roads built on soft clay subgrade after being opened to traffic. It has been widely recognized that the permanent deformation induced by long-term traffic loading is an important component of the total subgrade settlement. In order to understand traffic-induced deformation, numerous experimental researches have been carried out (e.g., Seed et al., 1955; Seed and McNeill, 1956; Hyde and Brown, 1976; Andersen et al., 1980; Yasuhara et al., 1982; Hyde and

*Corresponding author at: College of Civil Engineering and Architecture, Wenzhou University, Wenzhou 325035, PR China. Tel.: +86 577 8668 9687; fax: +86 577 8668 9611.

E-mail address: cleg19862008@163.com (J. Wang).

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Ward, 1985; Ansal and Erken, 1989; Hyde et al., 1993; Moses and Rao, 2003; Li et al., 2011; Guo et al., 2013, Wang et al., 2013), and many empirical formulas for deformation predictions have been proposed (e.g., Monismith et al., 1975; Li and Selig, 1996; Chai and Miura, 2002; Guo et al., 2013). Reviewing the previous laboratory studies, we find that one-way cyclic triaxial tests were mostly employed. In these one-way cyclic triaxial tests, the traffic loading was simulated by a single cyclic deviatoric stress only, which is purely compressive without reversal. Moreover, normally-consolidated clays were the main focus of these studies and overconsolidated clays were rarely considered. Furthermore, the drainage of pore water was usually prevented. However, with the progressive collection of experimental data and the development of more sophisticated laboratory apparatus, it is found that conditions corresponding to purely deviatoric cyclic loadings, normally-consolidated clays, and undrained conditions are not appropriate for reflecting the real conditions of traffic-induced subgrade deformation.

As previously stated, normally-consolidated soils have usually been tested rather than overconsolidated soils. In areas of soft clay, ground treatment is usually applied to improve the bearing capacity of subgrade clays. Among the various ground treatment methods for road construction, the surcharge preloading method is popular due to its effectiveness and convenience. In the process of surcharge preloading, the loading and unloading of surcharge leads to the appearance of overconsolidation on the subgrade clays. In general, these "new" overconsolidated subgrade clays are much better for road construction, due to reduced compressibility, increased strength, and increased stiffness. However, in laboratory investigations, overconsolidated clays show very distinctive dynamic properties compared to normally-consolidated clays. Fujiwara et al. (1985) and Fujiwara and Ue (1990) pointed out that the settlements of subgrade clays depend greatly on the overconsolidation ratio, which indicates the necessity for research on the traffic-induced deformation characteristics of overconsolidated clays.

Regarding the simulation of traffic loading, a single compressive cyclic deviatoric stress has been proven to be insufficient by many researchers (Powrie et al., 2007; Yang, 2009; Grabe, 2009; Rondon et al., 2009; Cai et al., 2013). As shown in Fig. 1 (Lekarp et al., 2000), the real traffic-induced dynamic stresses being applied on soil elements include a simultaneous cyclic variation in vertical normal stress ($\Delta\sigma_{11}$), horizontal normal stress ($\Delta\sigma_{22}$), and shear stress ($\Delta\sigma_{12}$), i.e., the varying stress field is composed of a varying deviatoric stress ($\Delta q = \Delta\sigma_{11} - \Delta\sigma_{22}$), a varying confining pressure ($\Delta\sigma_{22}$), and a varying shear stress ($\Delta\sigma_{12}$). The existence of cyclic shear stress will lead to the rotation of the principal stress axes, which can be investigated by hollow cylinder tests (Miura et al., 1986; Yang et al., 2007; Tong et al., 2010; Ishikawa et al., 2011; Xiao et al., 2013). The coupling effects of the cyclic vertical normal stress and the cyclic horizontal normal stress can be simulated by the simultaneous application of the cyclic deviatoric stress and the cyclic confining pressure, based on an advanced cyclic triaxial device which can apply

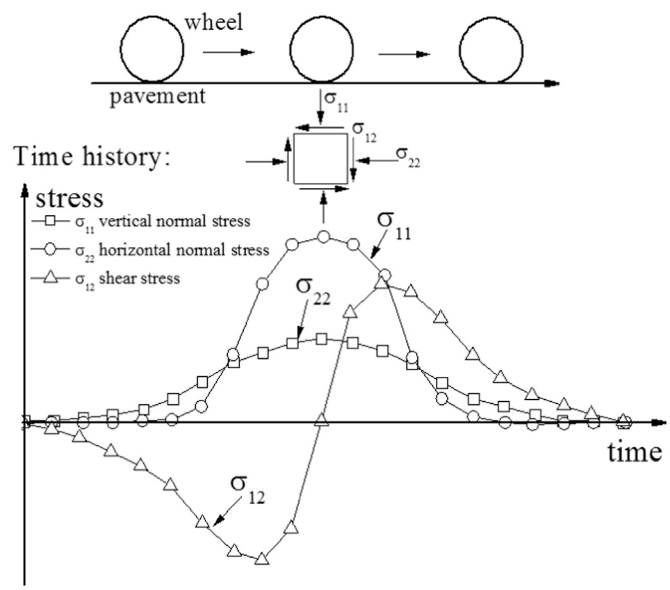

Fig. 1. Variation in stress components induced by traffic loading (Lekarp et al., 2000).

variable confining pressure (Wichtmann et al., 2007; Rondon et al., 2009, Cai et al., 2013).

As for the control of drainage, the so-called "undrained condition" is usually employed in short-term dynamic loadings such as earthquakes. However, traffic loading is long-term and the dissipation of pore water pressure will occur provided there are drainage paths. On the other hand, the permeability of clays is so low that full drainage is almost impossible. Many experimental investigations, such as those by Sekiguchi et al. (1981), Asaoka et al. (1992), Hyodo et al. (1992), Hyodo and Yasuhara (1988), Yasuhara et al. (1988), Sakai et al. (2003), and Cai et al. (2013), have observed that the excess pore water pressure in clays rises and dissipates simultaneously or alternatingly during traffic loading, indicating that the condition of clay subsoils sheared under traffic loading could be considered as semi-drained. In laboratory tests, this semi-drained state can be simulated by partially-drained conditions during the applications of cyclic loadings.

Cyclic triaxial tests with variable confining pressure (VCP tests) have been employed many times to investigate the undrained or drained behavior of coarse soils (Brown and Hyde, 1975; Nataatmadja and Parkin, 1989; Zaman et al., 1994; Simonsen and Isacsson, 2001; Wichtmann et al., 2007; Chazallon et al., 2006; Rondon et al., 2009). For example, based on many fully-drained tests on sands, Wichtmann et al. (2007) observed approximately double accumulation rates of permanent axial strain under certain stress paths with variable confining pressure, compared to the stress paths with constant confining pressure (CCP tests). Rondon et al. (2009) compared the drained behavior of unbound granular materials under several stress paths with or without cyclic confining pressure, and their results showed that the conventional cyclic triaxial tests with constant confining pressure may underestimate the traffic-induced settlements in some cases. All these studies indicated that the variable confining pressure plays an important