Soil Dynamics and Earthquake Engineering 78 (2015) 99–109

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Effects of cyclic confining pressure on the deformation characteristics of natural soft clay

Lei Sun [a], Chuan Gu [b,*], Peng Wang [b]

[a] Research Center of Coastal and Urban Geotechnical Engineering, Zhejiang University, Hangzhou 310027, PR China
[b] College of Civil Engineering and Architecture, Wenzhou University, Wenzhou 325035, PR China

ARTICLE INFO

Article history:
Received 30 January 2015
Received in revised form
16 July 2015
Accepted 17 July 2015
Available online 8 August 2015

Keywords:
Triaxial tests
Cyclic loads
Soft clay
Variable confining pressure
Residual strains

ABSTRACT

To investigate the coupling effects of cyclic deviator stress and cyclic confining pressure on the deformation behavior of natural soft clay under partially-drained conditions, a series of one-way cyclic triaxial tests with and without cyclic confining pressure were carried out. Test results show that, at the same amplitude of cyclic deviator stress, the increase of cyclic confining pressure amplitude will accelerate the accumulation of both permanent volumetric and axial strain significantly. The comparison between test results for different amplitudes of cyclic confining pressure shows that tests with a cyclic confining pressure corresponding to a stress path of $\eta^{ampl}=p^{ampl}/q^{ampl}=1$ lead to a 1.4 times larger permanent volumetric strain and a 1.2 times larger permanent axial strain compared to the conventional cyclic triaxial tests with constant confining pressure ($\eta^{ampl}=1/3$). In case of $\eta^{ampl}=2$ the permanent strains are found to be even 2.0 or 1.5 times larger compared to the standard tests. Finally, an empirical formula is proposed for the prediction of permanent axial deformations of natural soft clays under partially-drained conditions, considering the effects of cyclic confining pressure.

1. Introduction

The prediction and control of subgrade settlement is a key factor influencing the quality of road construction, especially in soft clay areas such as eastern coastal China. This is mostly because the natural soft clays have a high water content, large void ratios and low shear strength, promoting the development of permanent settlements of roads which are built upon such soft clay subgrades after opening to traffic. It has been recognized widely that the deformation induced by long-term traffic loading is an important component of the total subgrade settlement. In order to understand the traffic-induced deformation, lots of experimental studies (Seed et al. [1]; Seed and McNeill [2]; Hyde and Brown [3]; Andersen et al. [4]; Yasuhara et al. [5]; Hyde and Ward [6]; Ausal and Erken [7]; Hyde et al. [8]; Moses and Rao [9]; Li et al.[10]; Guo et al. [11]; Wang et al. [12]; Wang and Cai [13]) have been performed, and many empirical formulas for deformation prediction (Monismith et al. [14]; Li and Selig [15]; Chai and Miura [16]; Guo et al. [11]) have been proposed. A review of the previous studies reveals that one-way cyclic triaxial tests were mostly used. In these one-way cyclic triaxial tests, traffic loading was simulated by the application of cyclic deviatoric stress only, which is purely compressive without reversal, and drainage was usually prevented. However, along with the progressive collection of experimental data and development of more sophisticated laboratory testing devices, it was found that both the purely deviatoric cyclic loading and the undrained conditions are not appropriate to reflect the real conditions in the subgrade when subjected to traffic loading.

Regarding the control of drainage, the so-called "undrained condition" was usually used in studies involving short-term cyclic loadings such as those typical for earthquakes. However, traffic loading is long-term, a dissipation of excess pore water pressure will occur provided that there are drainage paths. On the other hand, the permeability of clays is so low that full drainage is almost impossible. Many experimental investigations, e.g. Sekiguchi et al. [17], Asaoka et al. [18], Hyodo et al. [19], Hyodo and Yasuhara [20], Yasuhara et al. [21], Sakai et al. [22], or Cai et al. [23] have shown that excess pore water pressure in clays arises and dissipates simultaneously or alternatingly during traffic loading, indicating that the condition of clayey subsoils subjected to traffic loading could be considered as partially-drained. In laboratory tests, this partially-drained state can be simulated by open drainage lines during the applications of cyclic loads.

For the simulation of traffic loading, compressive cyclic deviatoric stress cycles have been proved to be insufficient by many researchers (Powrie et al. [24]; Yang [25]; Grabe [26]; Rondon et al. [27]; Cai et al. [23]). As shown in Fig. 1 (Lekarp et al. [28]), the real traffic-induced dynamic stresses applied on soil elements include

* Corresponding author. Tel.: +86 577 8668 9687; fax: +86 577 8668 9611.
E-mail address: single_k@163.com (C. Gu).

http://dx.doi.org/10.1016/j.soildyn.2015.07.010
0267-7261/

a simultaneous cyclic variation of vertical normal stress ($\Delta\sigma_{11}$), horizontal normal stresses ($\Delta\sigma_{22}$) 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 result in the principal stress axes rotation, which can be investigated by hollow cylinder tests (Miura et al. [29]; Tong et al. [30]; Ishikawa et al. [31]; Xiao et al. [32]; Yang et al. [33], Cai et al. [34]). The coupling effects of cyclic vertical normal stress and cyclic horizontal normal stress can be simulated by the simultaneous application of cyclic deviatoric stress and cyclic confining pressure, using an advanced cyclic triaxial device which can apply variable confining pressure (Wichtmann et al. [35]; Rondon et al. [27]; Cai et al. [23]).

Cyclic triaxial tests with variable confining pressure (VCP tests) have been employed many times for the research of coarse soils (Brown and Hyde [36]; Nataatmadja and Parkin [37]; Zaman et al.

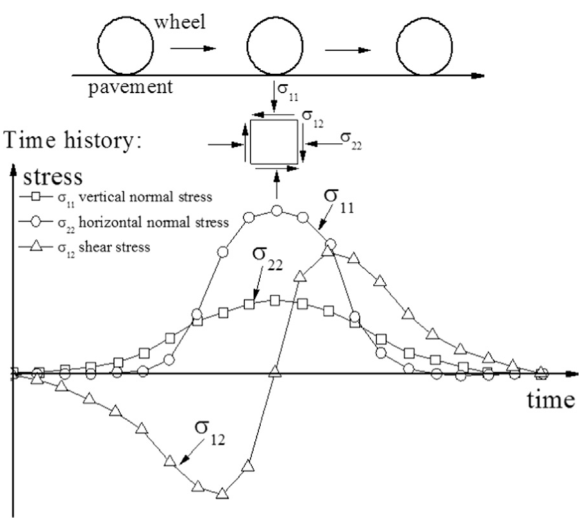

Fig. 1. Variation of stress components induced by traffic loads (Lekarp et al. [28], ASCE).

Table 1
Primary index properties of tested soft clay.

Index properties	Values
Specific gravity, G_s (g/cm^3)	2.72
Natural water content, w_n (%)	65.3–67.5
Initial density, ρ_0 (g/cm^3)	1.68–1.71
Initial void ratio, e_0	1.55–1.59
Liquid limit, w_L (%)	67.7
Plasticity index, I_p	37.2
Clay fraction, (%)	63.8
Silt fraction, (%)	93.4

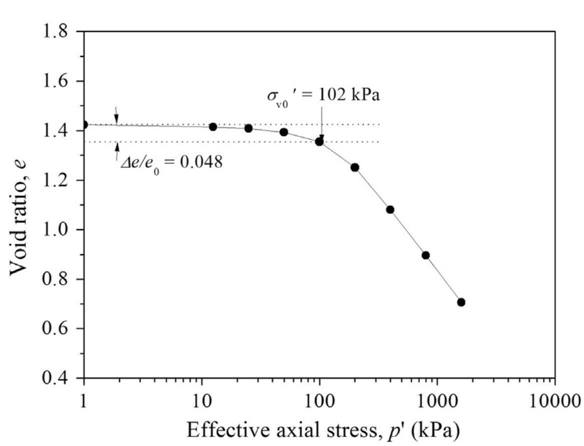

Fig. 2. Results of the consolidation test.

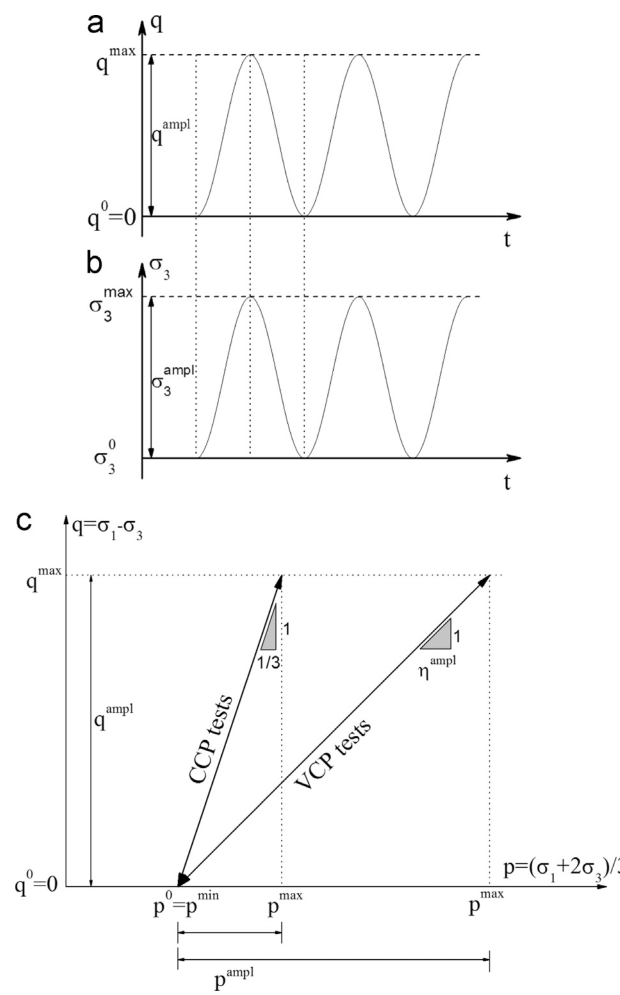

Fig. 3. (a) Time–history of cyclic deviatoric stress; (b) time–history of cyclic confining pressure; (c) stress paths employed by Cai et al. [23] ASCE).

Table 2
Test program in this study.

Test number	p_0' (kPa)	σ_3^{ampl}(kPa)	q^{ampl}(kPa)	CSR	η^{ampl}	Number of load cycles
P01	102	0	15	0.074	1/3	10,000
P02	102	10	15	0.074	1.0	10,000
P03	102	25	15	0.074	2.0	10,000
P04	102	0	21	0.103	1/3	10,000
P05	102	14	21	0.103	1.0	10,000
P06	102	35	21	0.103	2.0	10,000
P07	102	0	27	0.132	1/3	10,000
P08	102	18	27	0.132	1.0	10,000
P09	102	45	27	0.132	2.0	10,000
P10	102	0	36	0.176	1/3	10,000
P11	102	24	36	0.176	1.0	10,000
P12	102	60	36	0.176	2.0	10,000
P13	102	0	45	0.221	1/3	10,000
P14	102	30	45	0.221	1.0	10,000
P15	102	75	45	0.221	2.0	10,000
P16	102	0	54	0.265	1/3	10,000
P17	102	36	54	0.265	1.0	10,000
P18	102	90	54	0.265	2.0	10,000