

# One-way cyclic deformation behavior of natural soft clay under continuous principal stress rotation

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## Abstract

The design of traffic infrastructure foundations formations has traditionally been empirically rather than analytically based, and for the advanced methods currently in use, input parameters are typically determined from cyclic triaxial testing. In actual engineering, the stresses acting on soil elements induced by passing wheels are not as simple as cyclic triaxial loading. Due to real traffic loads involve the change of the principal stress direction in the ground, cyclic loading induced by traffic loading are typically one-way cyclic loading involved continuous principal stress rotation. Testing in a hollow cylinder apparatus (HCA) can impose the rotations in principal stress direction likely to be experienced by a soil element in the field, and may therefore be preferable to triaxial testing. The soil mechanics problem is one of understanding how soils respond to cyclic loading and applying this knowledge to foundation design. Non-linear stress–strain characteristics are a particular feature of the problem and have to be catered for design and evaluation. In this paper, a series of normally consolidated undrained HCA tests are performed to investigate the one-way cyclic deformation behavior of natural soft clay from Wenzhou, China. The principal stress axis continuously rotates while holding the deviator stress at a constant level. The tests results show that, the pore pressure, stress–strain hysteretic loop, dynamic modulus of the tested samples are significantly dependent on cyclic stress ratios and initial effective confining pressures. The value of degradation index becomes larger as the cyclic stress ratio and initial effective confining pressure increase. The threshold limit of the tested clay samples in terms of cyclic stress ratio can be considered as 0.255.

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**Keywords:** One-way cyclic loading; Continuous principal stress rotation; Natural soft clay; Deformation; Degradation

## 1. Introduction

Over the past decades, a large number of important traffic infrastructures, including highways, railways, and airport

runways, have been constructed on soft clay. This type of clay is widely distributed in the southeastern coastal cities of China. Because of its high water content, high compressibility, and low permeability, the soft clay is recognized as one of the most problematic soils. Deformation caused by cyclic loads has the potential to result in disaster from the instability of the foundations, which would results in huge economic loss and threatens human life. The prediction and control of subgrade settlements are key factors affecting

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the quality of the construction of traffic infrastructures in coastal cities. Investigating the dynamic response of soft clay under a complex stress path is particularly important.

As widely recognized, the permanent deformation induced by traffic loading is an important component of the total subgrade settlement. One-way cyclic loading is more typical for traffic loading and has been widely employed to study the dynamic behavior of soils under traffic loading. It means that cyclic loading is imposed in the vertical direction and has a semi-sine wave loading pattern. Over the past decades, many experimental studies have been carried out to investigate the properties of soft clay under one-way cyclic triaxial testing (Hyodo and Yashuhara, 1998; Moses et al., 2003; Guo et al., 2013; Cai et al., 2012; Gu et al., 2016). However, while the triaxial apparatus can control the two loading variables of confining stress and axial deviator stress, the major principle stress direction remained constant when it was parallel or perpendicular to the vertical direction. In reality, however, the real stresses acting on the soil elements induced by passing wheels are not as simple as the one-way cyclic triaxial loading suggests: real traffic loads involve change in the direction of the principal stress in the ground (Lekarp et al., 2000a, 2000b). For example, as described by Powrie et al. (2007), the changes in stress experienced by an element of soil below a railway track as a train passes are complex, and involve the cyclic rotation of the principal stress directions. As shown in Fig. 1 (Brown, 1996), there are pulses of vertical and horizontal stress accompanied by a double pulse of shear stress with a sign reversal on the vertical and horizontal planes. The cyclic stresses induced by passing wheels include varying axial normal stress ( $\Delta\sigma_{11}$ ), varying lateral normal stress ( $\Delta\sigma_{22}$ ), and varying shear stress ( $\Delta\sigma_{12}$ ); i.e., the varying stress field in subsoils under traffic loading is composed of

varying deviator stress ( $q = \Delta\sigma_{11} - \Delta\sigma_{22}$ ), varying confining pressure ( $\Delta\sigma_{22}$ ), and varying shear stress ( $\Delta\sigma_{12}$ ). In these conditions, conventional one-way cyclic triaxial loading cannot characterize cyclic stresses induced by real traffic loads, and soil element testing in uniaxial compression may lead to the underestimation of vertical strains.

To overcome the problems, equipment which reproduces the field situation should be selected. Complex facilities for pavements would be required, and a close match to field conditions by use of a hollow cylinder apparatus (HCA) has been proposed (Hight et al., 1983; Miura et al., 1986). This can offer four degrees of freedom for the loading parameters, including the axial load  $W$ , torque  $M_T$ , and internal and external pressures  $p_i$  and  $p_o$  such that complex stress path involving the change of the principal stress direction can be achieved. Testing in a HCA can impose the rotations in principal stress direction likely to be experienced by a soil element in the field, and may therefore be preferable to triaxial testing. Previous studies have elaborated the importance of principal stress rotation in traffic-induced stress characteristics (Chan and Brown, 1994; Momoya et al., 2005).

Research focused on granular material subjected to traffic loading almost always takes the principal stress rotation into consideration. Gräbe and Clayton (2009) investigated a number of reconstituted soils to simulate foundation materials on an existing heavy haul railway line and concluded that principal stress rotation cannot be ignored when evaluating permanent displacement of rail track foundations. Ishikawa et al. (2011) found that settlement in a moving-wheel loading test was much larger than the one in a single-point loading test. Gräbe and Clayton (2014) reported on the effects of principal stress rotation on the resilient behavior of track foundation materials. It was established that principal stress rotation reduces the resilient modulus of the materials compared with cyclic loading without principal stress rotation.

In recent years, many researchers have investigated the behavior of soft clay under the continuous stress rotation. Zhou and Xu (2014) carried out undrained principal stress rotation tests on intact soft clay to investigate the influence of initial shear stress on pore water pressure accumulation, strain and stiffness behavior. Wang et al. (2017) investigated the cyclic deformation behavior of natural soft clay using HCA, with different cyclic stress ratios and confining pressures considered. However, the studies focused on the stress path, which is a circle in the stress space of deviator stress versus the torsional shear stress. The two-way cyclic loading of deviator stress was also applied. To understand the effects of principal stress rotation on traffic load-induced settlement in soft subsoil below the subway tunnel, Xiao et al. (2013) examined the cumulative deformation and pore water pressure characteristics of saturated normally consolidated soft clays, but the influences of cyclic stress ratios ( $CSR$ ) were not taken into account.

As mentioned by Powrie et al. (2007), the magnitude of the stress cycle decreases with depth as the loads spread through the soil, and is especially relative to the in situ or

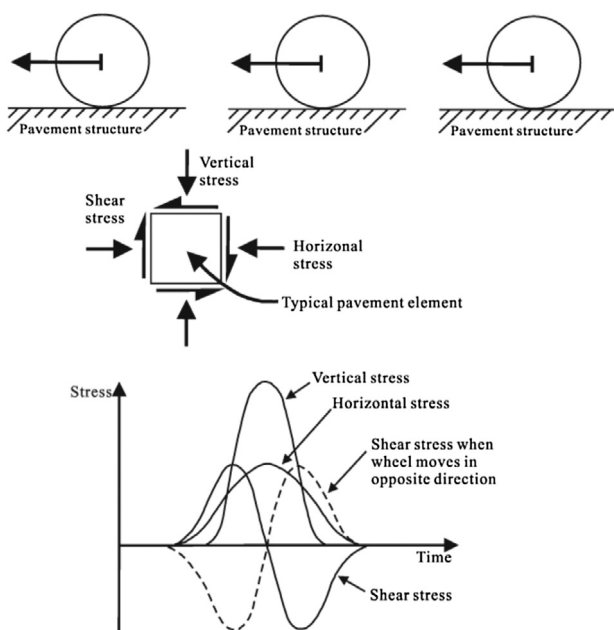


Fig. 1. Variation of stress components induced by moving wheel load (Brown, 1996).

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