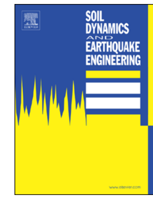
Soil Dynamics and Earthquake Engineering 69 (2015) 125–137

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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



# Stress attractors predicted by a high-cycle accumulation model confirmed by undrained cyclic triaxial tests

T. Wichtmann*, T. Triantafyllidis

*Karlsruhe Institute of Technology (KIT), Institute of Soil Mechanics and Rock Mechanics, Engler-Bunte-Ring 14, 76131 Karlsruhe, Germany*

ARTICLE INFO

*Article history:*
Received 5 September 2014
Received in revised form
12 October 2014
Accepted 13 October 2014

*Keywords:*
High-cycle accumulation (HCA) model
Undrained cyclic tests
Fine sand
Stress relaxation
Stress attractors

ABSTRACT

Depending on the boundary conditions a high-cyclic loading (=large number of cycles $N \geq 10^3$, small strain amplitudes $\varepsilon^{\text{ampl}} \leq 10^{-3}$) may either lead to strain accumulation or stress relaxation in the soil. This paper concentrates on stress relaxation. For a cyclic loading applied under undrained triaxial conditions, the high-cycle accumulation (HCA) model of Niemunis et al. [23] predicts a relaxation of average effective stress until a stress ratio $\eta^{\text{av}} = q^{\text{av}}/p^{\text{av}} = M_{cc}$ (triaxial compression) or $M_{ec}$ (extension) is reached. $M_{cc}$ and $M_{ec}$ are very similar to the critical stress ratios $M_c$ and $M_e$ known from monotonic shear tests. The average effective stresses finally reached after a sufficiently large number of cycles are called "stress attractors" herein. A zero effective stress state (liquefaction, $p^{\text{av}} = q^{\text{av}} = 0$) is obtained as a special case of a stress attractor. However, up to now the stress attractors predicted by the HCA model were based on the data from drained cyclic tests only. In the present study they have been approximately confirmed by stress relaxation experiments, i.e. undrained cyclic triaxial tests with stress or strain control. These tests have been performed on a fine sand, varying the initial values of density, mean pressure and stress ratio as well as the stress or strain amplitude.



## 1. Introduction

High-cycle accumulation (HCA) models [26,17,1,23,31] have been primarily developed in order to predict the permanent deformations in soils due to a cyclic loading with many cycles ($N \geq 10^3$) of small to intermediate strain amplitudes ($\varepsilon^{\text{ampl}} \leq 10^{-3}$). These models can be applied to predict the long-term settlements of foundations subjected to traffic loading (e.g. high-speed railways, magnetic levitation trains), wind and wave action (e.g. onshore and offshore wind power plants [45,52], coastal structures) or repeated filling and emptying processes (e.g. tanks, silos, watergates). Machine foundations (e.g. gas turbines [6]) are another practical example for a high-cyclic loading.

However, if some or all components of the strain tensor are fully or partly restricted, beside the accumulation of strain also a relaxation of stress takes place in the soil. Such stress relaxation occurs in many boundary value problems with high-cyclic loading, e.g. in the case of monopile foundations for offshore wind power plants which are subjected to horizontal wind and wave loading [45]. In that case a considerable redistribution of the horizontal stresses acting on the pile shaft may occur, in particular in the upper layers of soil. A redistribution of stress due to high-cyclic loading has been also observed for shallow foundations supporting a relatively rigid structure [52,44]. If some of the foundations are subjected to cycles with larger amplitudes and thus suffer larger accumulation, the average foundation stresses are redistributed towards the foundations with lower cyclic loads. Accordingly, the internal forces in the structure are altered, probably leading to damage.

Consequently, a HCA model must also properly describe the stress relaxation in the soil caused by the cyclic loading. As discussed in detail in the next section, the stress relaxation predicted by the HCA model of Niemunis et al. [23] depends on the *intensity* of strain accumulation $\dot{\varepsilon}^{\text{acc}}$, the *direction* of accumulation (cyclic flow rule, volumetric component $m_v$, deviatoric component $m_q$) and the elastic stiffness (bulk modulus $K$, shear modulus $G$). The quantities $\dot{\varepsilon}^{\text{acc}}$ and $K$, $G$ determine the *intensity* of stress relaxation [41]. The *stress attractors*, i.e. the average effective stresses reached by the relaxation path after a sufficiently large number of cycles, come out of the equations for the cyclic flow rule. According to these equations, for triaxial conditions the HCA model predicts a stress relaxation until the stress ratio $\eta^{\text{av}} = q^{\text{av}}/p^{\text{av}}$ is equal to the parameter $M$ of the cyclic flow rule ($M = M_{cc}$ for triaxial compression, $M = M_{ec}$ for extension).

The parameter $M$ used in the HCA model is usually calibrated from a series of drained cyclic tests with different average stress

* Corresponding author.
*E-mail addresses:* torsten.wichtmann@kit.edu (T. Wichtmann), theodoros.triantafyllidis@kit.edu (T. Triantafyllidis).

http://dx.doi.org/10.1016/j.soildyn.2014.10.013
0267-7261/

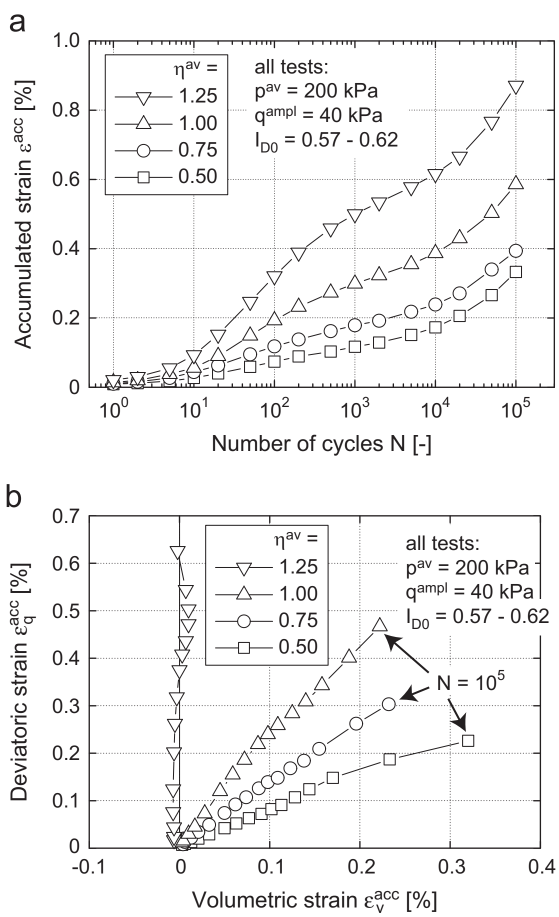



**Fig. 1.** (a) Strain accumulation curves $\varepsilon^{acc}(N)$ and (b) accumulated deviatoric strain $\varepsilon_q^{acc}$ versus accumulated volumetric strain $\varepsilon_v^{acc}$ measured in drained cyclic triaxial tests on the fine sand with different average stress ratios $\eta^{av}$.

ratios [39,42]. Fig. 1 presents the results of such a test series performed on the fine sand ($d_{50}$=0.14 mm, $C_u$=1.5, $e_{\min}=0.677$, $e_{\max}=1.054$) used in the present study. In those tests, medium dense samples with $I_{D0}=(e_{\max}-e)/(e_{\max}-e_{\min})=0.57$–$0.62$ were subjected to $10^5$ cycles. The average mean pressure was $p^{av}=200$ kPa and the stress amplitude was $q^{ampl}=40$ kPa in all tests. Stress ratios $\eta^{av}$ between 0.5 and 1.25 were tested. While Fig. 1a presents the curves of accumulated strain $\varepsilon^{acc}$ (with $\varepsilon=\sqrt{(\varepsilon_1)^2+2(\varepsilon_3)^2}$) versus the number of cycles $N$, the accumulated deviatoric strain $\varepsilon_q^{acc}$ is plotted versus the accumulated volumetric strain $\varepsilon_v^{acc}$ in Fig. 1b, with $\varepsilon_v=\varepsilon_1+2\varepsilon_3$ and $\varepsilon_q=2/3(\varepsilon_1-\varepsilon_3)$. The parameter $M$ used in the cyclic flow rule corresponds to the average stress ratio $\eta^{av}$ for which the accumulation is purely deviatoric, i.e. no volumetric strain accumulation takes place at that stress ratio ($\dot{\varepsilon}_v^{acc}=0$). From the data in Fig. 1b, a value $M=M_{cc}=1.25$ can be derived, corresponding to a critical friction angle of $\varphi_{cc}=31.1^{\circ}$. The corresponding lines in the $p$–$q$ plane, inclined by $M_{cc}$ for triaxial compression or $M_{ec}$ for triaxial extension, are denoted as "zero volumetric accumulation (drained)" lines (ZVADL) in the following. The $M_{cc}$ value obtained from Fig. 1b is in good accordance with the literature [22,3,39,42]. Note that the parameters $M_{cc}$ and $M_{ec}$ used in the HCA model are similar but need not be identical to the critical stress ratios $M_c$ and $M_e$ obtained from monotonic shear tests [42]. Therefore, the ZVADL lies close to the critical state line (CSL) from monotonic tests.

The stress relaxation predicted by the HCA model proceeds until the average effective stress path reaches the ZVADL. However, the assumption of the ZVADL as a stress attractor is only based on drained cyclic test data as that shown in Fig. 1b. Up to now this assumption has been confirmed in stress relaxation experiments for special cases only, i.e. for triaxial test conditions leading to a zero effective stress state (liquefaction, $p^{av}=q^{av}=0$) after a sufficiently large number of cycles. The ZVADL as a stress attractor can be checked by undrained (constant volume) triaxial tests with stress cycles applied at an average stress ratio $\eta^{av}>0$. Such examination is the purpose of the experimental study documented in this paper.

All samples (diameter $d$=100 mm, height $h$=100 mm) were prepared by air pluviation and tested under fully water-saturated conditions. The loading was applied very slowly (displacement rate 0.05 mm/min) by a load press driven by an electrical motor, controlling the minimum and maximum stresses.

## 2. Prediction of strain accumulation or stress relaxation by the HCA model

In the following, the prediction of strain accumulation or stress relaxation by the HCA model is recapitulated for the simple boundary value problem of an axisymmetric triaxial test. For axisymmetric element tests it is convenient to write the basic equations of the HCA model with Roscoe's invariants:

$$\dot{p}=K(\dot{\varepsilon}_v-\dot{\varepsilon}^{acc}m_v) \tag{1}$$

$$\dot{q}=3G(\dot{\varepsilon}_q-\dot{\varepsilon}^{acc}m_q) \tag{2}$$

In contrast to conventional constitutive models, HCA models predict only the cumulative portions of stress or strain. Therefore, in the context of HCA models the dot over a symbol means a derivative with respect to the number of cycles $N$ (instead of time $t$), i.e. $\dot{\sqcup}=\partial\sqcup/\partial N$ or an increment per cycle. In Eqs. (1) and (2), the rates of mean pressure $\dot{p}=(\dot{\sigma}_1+2\dot{\sigma}_3)/3$ and deviatoric stress $\dot{q}=\dot{\sigma}_1-\dot{\sigma}_3$ are interrelated with the rates of volumetric strain $\dot{\varepsilon}_v$ and deviatoric strain $\dot{\varepsilon}_q$ by an elastic stiffness described by bulk modulus $K=E/3/(1-2\nu)$ and shear modulus $G=E/2/(1+\nu)$. Omitting the plastic strain rate (see [23]) in Eqs. (1) and (2) is legitimate for homogeneous stress fields.

The intensity of accumulation $\dot{\varepsilon}^{acc}$ is calculated as the product of six functions, considering the influences of strain amplitude, void ratio, average stress, cyclic preloading and polarization changes [23,38,40]. The equations for the volumetric ($m_v$) and deviatoric ($m_q$) portions of the cyclic flow rule are adapted from the Modified Cam Clay (MCC) model [39,42]:

$$m_v=f\left[1-\frac{(\eta^{av})^2}{M^2}\right] \tag{3}$$

$$m_q=2f\frac{\eta^{av}}{M^2} \tag{4}$$

with

$$f=\frac{1}{\sqrt{\frac{1}{3}\left[1-\frac{(\eta^{av})^2}{M^2}\right]^2+6\left(\frac{\eta^{av}}{M^2}\right)^2}} \tag{5}$$

$$M=FM_{cc} \tag{6}$$

$$F=\begin{cases}1+M_{ec}/3 & \text{for } \eta^{av}\le M_{ec}\\ 1+\eta^{av}/3 & \text{for } M_{ec}<\eta^{av}<0\\ 1 & \text{for } \eta^{av}\ge 0\end{cases} \tag{7}$$