Computers and Geotechnics 62 (2014) 232–243

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Discrete modeling of strain accumulation in granular soils under low amplitude cyclic loading

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ARTICLE INFO

Article history:
Received 7 January 2014
Received in revised form 28 June 2014
Accepted 27 July 2014
Available online 24 August 2014

Keywords:
Granular soils
Cyclic loading
Low amplitude
High frequency
Strain accumulation
Discrete element method

ABSTRACT

An advanced understanding of the strain accumulation phenomenon in granular soils subjected to low amplitude cyclic loading with relatively high frequency is needed to enhance the ability to predict the settlement of granular soils induced by vibrations. In the current study, the discrete element method is used to study this phenomenon. A loose and a medium dense sample composed of a relatively large number of spheres are considered. A series of stress controlled cyclic triaxial tests with different excitation amplitudes and frequencies is performed on these samples at different static stress states. The response of these samples at the macroscopic and microscopic scales is analyzed. The sample density, the cyclic stress amplitude and the static stress state importantly affect strain accumulation. However, the cyclic excitation frequency has a small effect on strain accumulation. At the microscopic scale, frictional sliding occurring at a few contacts continuously dissipates energy and the fraction of these contacts varies periodically during cyclic loading. The coordination number of these samples increases slightly as strain accumulates. However, the anisotropy remains almost constant during low amplitude cyclic excitation. A qualitatively good agreement between numerical and experimental results is found.

1. Introduction

Granular soils under the foundation of buildings are subjected to vibrations arising from several sources such as road and railway traffic, construction activities and reciprocating machines. Vibrations cause the stress state in these media to vary cyclically with low amplitude compared to the static stress state. The excitation frequency can be typically up to 20 Hz for road traffic induced vibrations [1] and 150 Hz for railway traffic induced vibrations [2]. Due to hysteresis, each loading cycle results in a small residual deformation. This deformation accumulates with increasing number of cycles and may become significant after a large number of cycles, causing differential settlement of soils under foundations and hence damage to buildings. Several phenomenological models have been proposed to predict the differential settlement of granular media subjected to low amplitude cyclic loading [3–6], which are based on a large number of laboratory experiments. These models present significant drawbacks as some of their parameters do not have a clear physical meaning and are difficult to identify. Consequently, there is still an increasing need to advance the understanding of strain accumulation in granular materials under low amplitude cyclic loading and the ability to predict this phenomenon.

Many laboratory experiments have been conducted to study strain accumulation in granular media under cyclic loading. Wichtmann et al. [7,8] performed a complete experimental study of strain accumulation in sand samples: low amplitude cyclic triaxial tests with a large number of cycles (up to 10^5) were conducted at low frequencies varying from 0.05 Hz to 2 Hz. It was shown that strain accumulation in sand samples depends on several factors such as the sample density, the cyclic stress amplitude, the cyclic frequency, the average stress, the loading history and the grain size distribution. Cyclic triaxial tests on sand samples at higher frequencies were performed by Karg [6] and Rascol [9]. Karg has found that strain accumulation is not influenced by loading frequencies ranging from 2 to 10 Hz. His study turned out, however, that the performance of cyclic tests is significantly reduced at frequencies above 2 Hz as the pneumatic loading system could not follow exactly the sinusoidal loading curve. Suiker [10] and Indraratna et al. [11] studied strain accumulation in ballast samples through high amplitude cyclic triaxial tests at frequencies up to 40 Hz. These studies showed that strain accumulation in ballast samples is not influenced by cyclic frequencies under 5 Hz [10],

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http://dx.doi.org/10.1016/j.compgeo.2014.07.015
0266-352X/

but it is importantly influenced by frequencies ranging from 10 to 40 Hz [11].

The discrete element method (DEM) pioneered by Cundall and Strack [12] can complement laboratory experiments. O'Sullivan [13] gives a full description of this method. The DEM is able to simulate complex loading tests which are difficult to conduct experimentally and enables access to information at the particle level so the local behavior at the particle scale can be investigated. This method has been widely used to simulate monotonic and cyclic loading tests. Most of cyclic loading tests were performed with high amplitude. Alonso-Marroquín et al. [14,15] simulated cyclic tests with large amplitude on assemblies of polygons to study the ratcheting phenomenon in granular media. A few simulations of low amplitude cyclic tests are found. Recently, Hu et al. [16,17] have reported numerical simulations of low amplitude cyclic biaxial tests at constant mean stress on 2D loose granular samples composed of a relatively small number (896) of disks. They focused on the evolution of the internal structure of 2D granular media during low amplitude cyclic loading at low frequencies (<1 Hz). The effect of the average stress state and cyclic stress amplitude on the accumulation of the axial strain was also analyzed. It was not shown, however, how these factors influence the accumulation of the volumetric and deviatoric strains and the direction of strain accumulation.

The present paper presents a study of strain accumulation in 3D granular samples under the action of traffic induced vibrations by simulating low amplitude cyclic triaxial tests at relatively high frequency. While it is difficult to conduct low amplitude cyclic tests at high frequency in the laboratory, the DEM is an alternative option to simulate this kind of cyclic tests. Moreover, this method allows an investigation of the microscopic behavior of granular samples during cyclic excitation. The first purpose of the current study is to analyze the influence of different factors such as the sample density, the amplitude and the frequency of the cyclic excitation and the static stress state on strain accumulation in granular soils. For this purpose, the DEM has a great advantage compared to laboratory experiments since different loadings can be applied on the same sample. The second purpose is to investigate the energetic behavior and the evolution of the internal structure of granular materials during low amplitude cyclic loading. The main novelty of the current study compared to the study of Hu et al. [16,17] resides in the high frequency of cyclic loading and the more detailed analysis of strain accumulation. In addition, 3D samples considered in the current study reproduce better the packing density and the deformation of real granular materials and allow a confrontation between numerical results and experimental data reported in [7,8].

This paper is organized as follows. Section 2 presents two numerical samples considered in the current study. The behavior of these samples during triaxial compression tests is briefly discussed in Section 3. Strain accumulation in these samples during low amplitude cyclic triaxial tests and the influence of different parameters on this phenomenon are analyzed in Section 4.

2. Numerical samples

The software PFC3D [18] is used to simulate low amplitude cyclic triaxial tests on 3D granular samples. To simulate a large number of loading cycles within a reasonable computation time, spherical non-crushable particles, a linear contact model and a rigid wall boundary are adopted in the current study. Two samples A and B with different densities are created, each of which is composed of 10,342 spheres with mass density $\rho = 2650\ \text{kg/m}^3$. The particle size for both samples is uniformly distributed from $d_{\min} = 4$ mm to $d_{\max} = 8$ mm. This particle size is larger than that of actual sand samples whose maximum grain diameter is about 2 mm. In the DEM, the time step is proportional to the square root of the particle mass. As a result, a very small time step (typically of the order 10^{-7} s) is required to simulate samples with particle size smaller than 2 mm; therefore, computation time is very long. Samples A and B correspond actually to fine gravels. They are used to keep computation time reasonable.

The parameters of the linear contact model are the normal and tangential stiffnesses $k_n = k_s = 5 \times 10^6$ N/m and the friction coefficient $\mu = 0.6$. No viscous damping is added at the contact points; therefore, only friction dissipates energy in the samples. To justify the quasi-rigidity assumption for particles, the ratio $k_n/(\sigma_o d)$ with σ_o the confinement stress and d the mean particle diameter must be sufficiently high. In the current study $\sigma_o \leqslant 100$ kPa hence $k_n/(\sigma_o d) > 8 \times 10^3$ which is acceptable. The resulting time step is of the order 10^{-6} s.

The particles of each sample are randomly generated in a parallelepiped composed of 6 rigid walls. The samples are then isotropically compacted until reaching a given target stress state. To obtain different densities, the friction coefficient μ for samples A and B is set to 0.6 and 0.3 during the compaction phase, respectively. When about 90% of the target stress state is reached, μ is reset to its original value. Fig. 1 shows sample A after compaction with height $H = 17.0$ cm and width $L = 11.4$ cm.

Particle breakage might occur in granular materials during cyclic loading, particularly at high amplitude and high hydrostatic stress [11,19]. It can be expected that only a small number of particles would be crushed during low amplitude cyclic loading at low hydrostatic stress. As indicated in [10], particle breakage is indeed small in ballast samples subjected to high amplitude cyclic loading tests at a hydrostatic stress $p < 193$ kPa. Donohue et al. [19] observed that the amount of particle breakage in carbonate sand, which is quite fragile, is small during cyclic loading tests at a hydrostatic stress $p = 100$ kPa. Consequently, it is relevant to neglect particle breakage in the current study.

The rigid wall boundary is used in the current study as it is easily implemented and a small computational effort is needed. However, this rigid boundary inhibits the natural development of shear bands that are clearly observed during physical triaxial compression tests. To enable shear bands to develop, a stress controlled membrane has been introduced in [20,21], which simulates the flexible latex membrane used in physical tests. However, the implementation of this membrane boundary is quite complex, in particular for 3D materials, and a significant computational effort is needed to update it during simulation. The stress controlled membrane has been used by Hu et al. [17] to simulate low

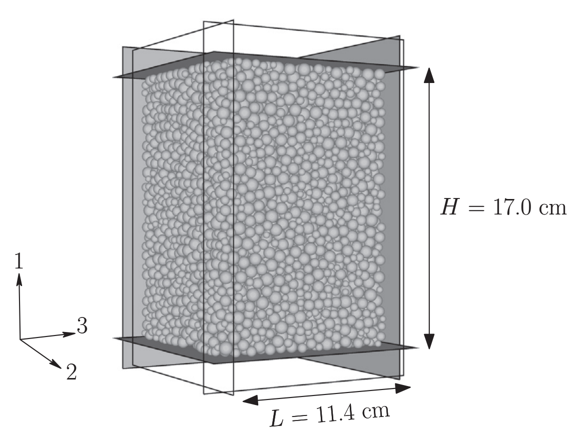

Fig. 1. Configuration of sample A contained by a parallelepiped box composed of 6 rigid walls.