Advanced Powder Technology 28 (2017) 155–166

Contents lists available at ScienceDirect

Advanced Powder Technology

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

Original Research Paper

Experimental and numerical study of cylindrical triaxial test on mono-sized glass beads under quasi-static loading condition

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ARTICLE INFO

Article history:
Received 3 May 2016
Received in revised form 20 September 2016
Accepted 23 September 2016
Available online 5 October 2016

Keywords:
Triaxial test
Discrete element method
Shear behavior
Friction
Rolling resistance
Homogeneous
Glass beads

ABSTRACT

This paper aims at studying the shear behavior of homogeneous granular materials by conventional triaxial test. The work is performed both in laboratory tests and by discrete element method simulations. Conventional triaxial tests are performed on glass beads packing, while a cylindrical rigid wall boundary condition based on lame formula and a series of procedures are proposed to simulate the conventional triaxial test. The experimental results on dry and saturated glass beads samples have been studied to find out the effect of saturation condition on the shear behavior. The comparisons between experimental and numerical results show that the numerical model can reproduce deviatoric curves satisfactorily in experimental conditions as long as experimental sample remains cylindrical. It correctly describes the volumetric strains of a numerical sample up to the peak value. Additionally, a parametric study on the influence of main micromechanical parameters has been carried out, which has been compared to experimental tests with glass beads of different textures. The comparison highlights the significant effect of friction coefficients and rolling resistance coefficients on global behavior of granular materials.

1. Introduction

Granular materials exist widely in nature and the industrial domain. The engineering applications of granular materials require us to have a better understanding of their physical properties. Shear behavior is a key characteristic in geomechanics to design civil engineering structures which might cause accidents like slope instability, landslide, avalanche, etc. Usually, it is studied by laboratory tests such as direct shear test, ring shear test, triaxial test, etc. Among these laboratory tests, triaxial test is one of the most popular laboratory tests to study shear behavior of experimental samples [1–4]. However, triaxial test in laboratory often require abundant experiment works which cost people lots of time and money. Therefore, computational approaches are increasingly employed to share assignments of experiment tests.

Discrete element method (DEM) was first proposed by Cundall and Strack [5]. This method is demonstrated as an efficient tool to study granular materials not only from a macro-scale view point, but also at the grain scale of granular material. Every time step, the contact between grains are first detected, then the contact forces are computed to update velocity and displacement via acceleration of each particle. DEM has been used to study a wide variety of problems of granular materials [6–10], etc.

Simulation of triaxial test has been studied by DEM analysts for a long time: Iwashita et al. [11] studied shear behavior by simulating triaxial test in 2D DEM. Kumar et al. [12] studied the effects of poly-dispersity on micro-macro behavior of granular assemblies under different deformation paths by true triaxial test with 3D DEM. Belheine et al. [13] studied triaxial test in drained conditions using DEM in consideration of rolling resistance. DEM simulation of triaxial test has been performed under different boundary conditions. Some researchers simulated triaxial test with membrane boundary condition which allows representation of the irregular deformation of samples during tests. For example, Lee et al. [14] used a membrane boundary condition combined of polyhedral discrete elements. Kozicki and Tejchman used membrane boundary to show clear shear band [15,16]. Some researchers used periodic boundary conditions [17,18] with Representative Elementary Volume (REV). In such cases, the number of particles must be large

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http://dx.doi.org/10.1016/j.apt.2016.09.006
0921-8831/

Nomenclature

σ_1	axial stress	Δt	time step
$\sigma_{2,3}$	lateral stress	Δr	variation of radius
p'_0	effective confining pressure	P_1	lateral pressure
u_c	pore pressure	P_2	target pressure
$e = \frac{V_v}{V_s}$	void ratio	r_1	internal radius of cylinder
ρ	density	r_2	external radius of cylinder
δ	overlap between particles	I	inertia number
R_{ij}	effective radius	$\dot{\varepsilon}$	shear strain rate
γ_n	normal damping coefficient	q	deviatoric stress
v	Poisson's ratio	p'	effective confining pressure
w	angular velocities of particle	M	ratio between q and p'
E	Young's Modulus	φ	friction angle
μ	friction coefficient	m	mass of particle
CoR	coefficient of restitution	S	standard deviation
μ_{rgg}	rolling resistance coefficient		

enough to ensure the representativity of the DEM packing [19]. Other researchers simulated conventional triaxial test by using rigid boundary conditions. Although, the rigid cylindrical boundary condition can't reflect well the deformation of samples during the late stage of triaxal test, it is easier than membrane condition to implement [20–23].

Besides, most research focuses either on experiments or on numerical simulations, fewer people present a comparison between experiments and numerical simulations carried out in the same conditions. It is worth mentioning that glass beads or steel beads can be used as elementary grains of experimental tests, which makes it possible for comparisons of DEM simulations [21,24–26].

With this background, a rigid cylindrical boundary condition controlled by Lame formula has been first proposed to simulate conventional triaxial test ($\sigma 2 = \sigma 3$). This rigid cylindrical boundary condition helps us to control lateral confining pressure as accurate as possible. Then, the simulation results have been compared with experimental tests in identical conditions (same cell dimensions, same number and size of particles, same confining pressures, etc). And finally, further research into micromechanical parameters' effect on overall behavior of materials has also been conducted.

2. Experiment test

2.1. Test program

In the experimental study, conventional triaxial tests ($\sigma_1, \sigma_2 = \sigma_3$) were carried out on mono-sized spherical glass beads which can be considered as ideal particles and easily simulated by DEM. The glass beads were supplied by LABOMAT ESSOR/SILI company in France. The size distribution of glass beads is shown in Table 1. For each test, new glass beads were systematically used to avoid deformation after repeated use [24]. Several effective confining pressures ($p'_0 = 50$ kPa, 100 kPa, 200 kPa) were tested in dry and saturated conditions. The main characteristics of the tests are listed in Table 2. Each test condition was repeated three times.

2.2. Test preparation

The experimental specimens were formed into a cylindrical shape 50 mm in diameter and 125 mm tall. The average density was $\rho = 2530\ \text{kg/m}^3$. The glass beads were 4 mm which is an appropriate diameter to prepare the dense sample and to show apparent shear band comparing to other diameters.

Each specimen was prepared using the following procedure:

- Step 1, a deformable latex membrane was put inside a metal mold.
- Step 2, glass beads were deposited in the mold by pluviation method and tapped with a small hammer to make specimens as dense as possible.
- Step 3, two permeable stones were put separately at the bottom and on the top of the specimen. A loading cap was then used to close the mold.
- Step 4, the metal mold was removed after a suction applied by a vacuum pump to ensure cohesion of granular medium. The void ratio of specimens reached 0.58 ± 0.01.
- Step 5, the specimen was then placed in a triaxial cell.

For saturated conditions, deaerated water was injected into samples. The volume of injected water was three times the volume of specimen in order to improve the saturation level of samples by avoiding air bubbles inside the specimen [24]. The specimen can be considered well saturated when the value of Skempton coefficient was greater than 0.95. After that, an isotropic consolidation procedure was imposed with a given effective confining pressure ($p'_0 = 50$ kPa, 100 kPa, 200 kPa). The bottom press plate rose upwards to exert a vertical force up to an axial strain about 15%. The press plate velocity was then chosen as 0.1 mm/min in order to perform tests in quasi-static conditions [27].

Fig. 1 shows a series of photos for an experimental sample at different axial strains. Fig. 2 shows the deviatoric stress of a typical experimental result corresponding to the different stages during the triaxial test, we can see that the shape of sample remains cylinder form almost until 5% axial strain, while the peak value occurs at 2% of axial strain. Shear band begins to appear almost at 5% axial strain. Similar observations have been presented by Higo et al. [28] who observed their experimental samples remaining cylinder form until 4–8% axial strain. So a cylindrical shape can be sufficient to describe the shape of a conventional triaxial test sample up to at least the peak value (the highest value of deviatoric stress).

Table 1
Size distribution of glass beads used in the research.

Size percentage	<3.8 mm	3.8–3.9 mm	3.9–4.0 mm	>4.0 mm
%	1.08	14.05	83.57	1.30