Influence of microstructural characteristics on the strength of granular media

Influence des caractéristiques microstructurales sur la résistance des milieux granulaires

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ABSTRACT: Triaxial tests on granular media constituted by spherical particles are simulated using the discrete element method. The analyses at grains scale suggest that the internal friction angle of granular media depends both on friction in the contact points and interlocking among grains. It is observed that only part of the friction resistance in contacts is developed. Differences in the granular structure and in the interlocking of grains lead to variations of the internal friction angle in compression and in extension. Higher strength corresponds to samples with high geometrical anisotropy of the distribution of contact points on the surface of grains.

1 INTRODUCTION

Granular materials occupy a prominent place in human activity in general and especially in geomechanics. These materials are constituted by agglomerates of individual particles that interact in their points of contact. To consider this discontinuous nature, it is necessary to investigate the phenomena taking place at the scale of the grains.

In order to explain the overall strength, some micro characteristics of dry granular media (spheres assemblies) during triaxial tests are analyzed. Numerical simulations are carried out using Discrete Element Method (DEM) (Cundall and Strack 1979). The contributions of interparticle friction (in contact points) and the interlocking of grains (observed through geometrical anisotropy) to global shear strength are assessed.

2 DESCRIPTION OF GRANULAR MEDIA

2.1 *Overall strength*

According to Mohr-Coulomb criteria, the overall strength of a dry granular material can be expressed in terms of an internal friction angle (φ). This angle is affected by interparticle friction, grain size distribution, interlocking, initial porosity, applied stresses and rate of loading (Rowe 1962, Lambe and Whitman 1972, Bolton 1986). In geotechnical practice, attention must be paid to peak and residual strength both in compression and extension.

2.2 *Microscopic description*

To describe granular media, generalized concepts resorting to the language of probability and statistics can be used (Matheron 1967, Auvinet 1986). The present research focuses on geometrical and mechanical anisotropies (Rothenburg and Bathurst 1989, Cambou *et al.* 2002) and their relation to global behavior.

Geometrical anisotropy can be studied examining the distribution of contacts on the surface of grains. The distribution of the orientation of normal vectors to tangent planes in contact points (Fig. 1) can be represented by a function $\Gamma(\alpha,\beta)$ satisfying Ec. 1, where Ω is a sphere with unitary radius and the elementary solid angle is $\omega = \cos\alpha d\beta d\alpha$.

$$\int_{\Omega}\Gamma(\alpha,\beta)d\omega = 1 \qquad (1)$$

For a uniform distribution in β, a simpler function $\Gamma(\alpha)$ can be used, such that:

$$\int_{-\pi/2}^{\pi/2}\Gamma(\alpha)\cos\alpha d\alpha = 1 \qquad (2)$$

Mechanical anisotropy is associated to the non-uniform orientation of contact forces (Fig. 1). It can be represented by a mixed probability density $f_{\delta}(d)$, where δ is the angle between the contact force and the normal direction. The limit frictional force developed is $F^{\{s\}} = F^{\{n\}} * tan(\delta)$ and the interparticle friction angle is $\phi = atan(\mu)$. The probability of sliding of contacts is $P[\delta = \phi]$, being μ the interparticle friction coefficient.

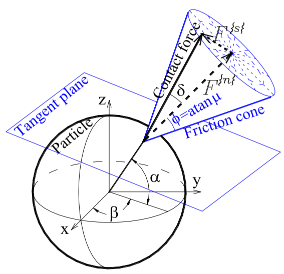

Figure 1. Location of a point of contact and force orientation

3 SIMULATION PROCEDURE

Granular samples are formed placing spherical particles within a cubic box using a geometric algorithm (Auvinet 1975). Subsequently, triaxial tests are performed using PFC^{3D} (Itasca 2008), a DEM computer program.

The following parameters are considered: number of particles in each sample: 30 000; mass density: 2 600 kg/m^3; grain size: monosized and linear continuous distribution with D_{max}/D_{min}=10; contact model: linear; normal contact stiffness: 10^7 N/m; shear contact stiffness: 10^7 N/m; friction coefficient: μ=0.1, 0.3 and 0.7 (for continuous grain size distribution only μ=0.7 was used).

4 RESULTS

4.1 *Macroscopic results*

Fig. 2 shows typical stress-strain and volumetric strain curves. In the last stage of compression and extension paths, stress and volumetric strain are approximatley constants and a critical state is reached. Loading and unloading cycles in compression and extension were assessed in another paper (Sánchez 2017).

Internal friction angle is obtained as φ=arcsin[(σ_1- σ_3)/(σ_1+ σ_3)] for the last point both in compression and extension. Peak strength is not observed in all materials and only residual strength is considered. Results are presented in Table 1.

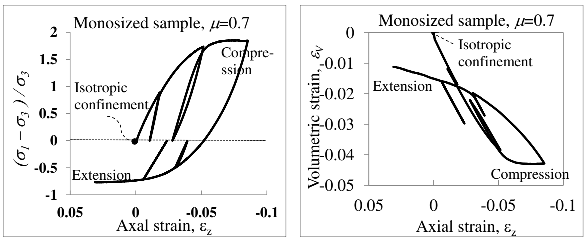

Figure 2. Stress strain and volumetric strain curves of a simulated triaxial test.

Table 1. Results of simulated triaxial tests

Grain size	μ	ϕ (°)	n initial	φ (°) compression	φ (°) extension
Monosized	0.1	5.7	0.36	15.2	18.9
Monosized	0.3	16.7	0.40	21.4	28.8
Monosized	0.7	35.0	0.41	28.3	33.4
Continuous	0.7	35.0	0.32	19.6	22.7

Different interparticle friction coefficients and grain size distributions lead to different initial sample porosities (n). A lack of conspicuous relationship between initial porosity and strength (φ) was observed for tested samples.

Interparticle friction angle ϕ=atan(μ) (Fig. 1) does not coincide with internal friction angle (φ). A higher φ is obtained in extension than in compression. For μ=0.7, continuous grain size sample presents lower φ value than monosized sample.

4.2 *Micromechanical results*

Contact forces act in many directions but the maximum friction shear force is reached only for δ=ϕ. Mixed probability density $f_\delta(d)$ shows that in most contacts only part of frictional resistance in contacts is developed (Fig. 3). The actual mobilized interparticle friction can be represented by the average mobilized friction angle $\phi^*=\Sigma^N abs(\delta_i)/N$, where N is the number of contacts (Table 2). This angle is lower than the internal friction angle, evidencing a contribution of the skeleton of the granular medium due to grains interlocking.

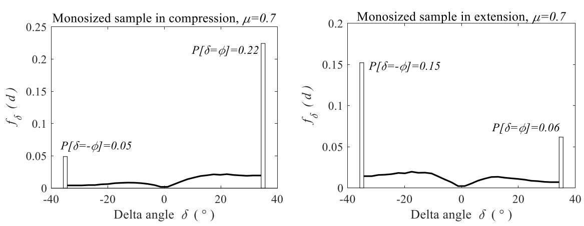

Figure 3. Mixed probability density $f_\delta(d)$ for a monosized sample.

Interlocking (φ^*) can be represented as $\varphi^*=\varphi-\phi^*$. For low friction coefficients (μ), interlocking provides most of the strength. For high μ values, contribution of interparticle friction (ϕ^*) is more significant. Interlocking is higher in extension than in compression due to the reorganization of the structure (Fig. 4). For continuous grain size distribution, interlocking is not observed because small particles work as rollers facilitating the displacements of the large ones.

Table 2. Contribution of interparticle friction and interlocking to global strength

Sample	Compression			Extension		
	φ (°)	ϕ* (°)	φ* (°)	φ (°)	ϕ* (°)	φ* (°)
Mon. μ=0.1	15.2	4.9	10.3	18.9	4.9	14.1
Mon. μ=0.3	21.4	12.9	8.5	28.8	12.6	16.2
Mon. μ =0.7	28.3	22.6	5.7	33.4	21.9	11.5
Cont. μ =0.7	20.3	20.5	0	22.7	20.2	2.5

In monosized samples, where a non-uniform repartition Γ(α) of points of contact is observed (geometrical anisotropy), high strength develops. Fig. 4 shows a concentration of points of contact near α=50° in compression and a concentration near α=0° in extension. This anisotropy is higher for monosized materials than for continuous grain size materials and this particular structure increases resistance.

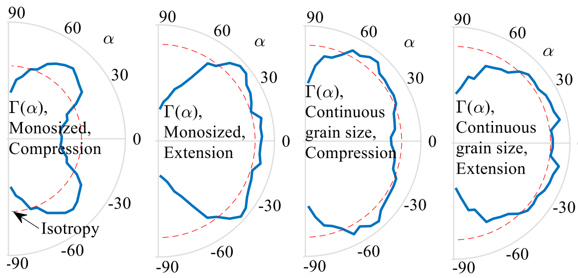

Figure 4. Geometrical anisotropy of repartition of contact points for different stress states in granular samples with μ=0.7.

5 CONCLUSION

The behavior of granular media was studied using a discrete approach. A variation of initial porosity with interparticle friction coefficient and grain size distribution was observed. The contributions of the friction in contact points and of the interlocking among grains related to the geometrical anisotropy were assessed. A higher interlocking in extension than in compression due to the reorganization of the structure was identified. Further research is required to obtain more general results.

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