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Influence of water content on the mechanical behavior of granular assemblies

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ABSTRACT: An explicit relation is developed to describe the capillary force in a doublet of two grains of different sizes as a function of the physical and geometrical characteristics. In particular, it depends on the inter-particle distance and on the volume of the liquid bridge. The modeling of capillary force is validated by experiments performed over a capillary doublet. From this theoretical modeling, we propose a local law of interaction by capillary force taking into account contact and friction between particles as well as the rupture of the liquid bridge. This local law is then implemented in a 3D code based on Discrete Element Method (DEM). This code is used to compute the macroscopic behavior of granular materials involving local interactions as capillary forces.

1 INTRODUCTION

The presence of water has important effects on the mechanical behavior of granular materials as powders, soils. This problem concerns several industrial and scientific domains such as pharmaceutical industry, soils sciences, civil engineering.

The effect of water is studied in the case of capillary cohesion in the pendular state, which corresponds to the existence of disconnected liquid bridges between grains. Most of the studies are done for monodisperse granular materials (grains of the same size) leading to some relations between the capillary force and physical and geometrical characteristics of the capillary doublet (Israelachvili 1992; Mikami et al. 1998). Extensions to the case of polydisperse granular materials (grains of different sizes) have been proposed as well (Willett et al. 2000). We consider this case and we study the capillary cohesion at the local scale in order to propose an explicit relation between the capillary force and the characteristics of the doublet that are easily accessible. This explicit relation must be simple enough for implementation in a numerical code in order to evaluate the influence of local capillary forces on the macroscopic behavior of granular assemblies.

We present also an application to the radial compression test of humid granular assemblies. Simulations show the influence of water on the macroscopic behavior of the assemblies.

2 CAPILLARY COHESION BETWEEN TWO GRAINS OF DIFFERENT SIZES

The capillary cohesion is studied at the local scale in a quasi-static configuration. The gravity effects are not considered.

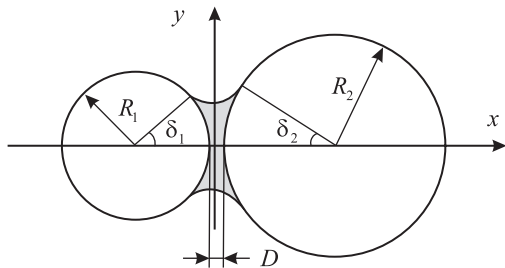


Figure 1. Geometrical description of a liquid bridge between grains of different sizes.

In the case of a doublet of two grains of different sizes, the liquid bridge takes an axially-symmetrical complex shape (Fig. 1). The shape depends on the pressure difference $\Delta p = p_{gas} - p_{liquid}$ across the gas-liquid interface and on the parameters describing the configuration of the capillary doublet. A first set of parameters concerns the physical characteristics of the constituents: the contact angle θ and the surface tension σ . Another set of parameters describes the geometrical characteristics: the sizes of the grains that are assumed to be smooth spheres of radii R_1 and R_2 , the inter-particle distance D , and the volume of the liquid bridge V .

The shape of the liquid bridge is described by the Laplace equation:

$$\Delta p = \sigma \left[-\frac{1}{y(x)\sqrt{1+y'^2(x)}} + \frac{y''(x)}{(1+y'^2(x))^{3/2}} \right] \quad (1)$$

Equation (1) is solved numerically to obtain the geometrical configuration of the liquid bridge. This



Figure 2. Example of capillary doublet used for experiments at the local scale.

numerical study is done for several values of parameters R_1 , R_2 , and θ . We compute the capillary force, the inter-particle distance and the liquid bridge volume for these different situations. In this way, we obtain a set of numerical solutions that connect the capillary force to the characteristics of the capillary doublet. In order to get a simple explicit relation between the capillary force and the characteristics of the capillary doublet, we fit the numerical solutions. We obtain a relation that is an extension to the polydisperse case of the expression proposed by Mikami et al. (1998) in the monodisperse case:

$$F = \pi \sigma \sqrt{R_1 R_2} \left[c + \exp \left(a \frac{D}{R_2} + b \right) \right] \quad (2)$$

The coefficients a , b , and c are functions of the liquid bridge volume V , of the contact angle θ , and of the radius of the largest grain R_2 :

$$\begin{aligned} a &= -1.1 \left(\frac{V}{R_2^3} \right)^{-0.53} \\ b &= \left(-0.148 \ln \left(\frac{V}{R_2^3} \right) - 0.96 \right) \theta^2 \\ &\quad - 0.0082 \ln \left(\frac{V}{R_2^3} \right) + 0.48 \\ c &= 0.0018 \ln \left(\frac{V}{R_2^3} \right) + 0.078 \end{aligned} \quad (3)$$

The relation (2) has been successfully compared to exact numerical data obtained from the integration of the Laplace-Young equation and experimental results reported by Willett et al. (2000).

Experiments at the local scale are carried out on capillary doublets composed of stainless steel balls (Fig. 2). A liquid bridge of a given volume V is introduced between the balls using a micro-syringe. The inter-particle distance D is controlled by a micrometer screw. For several values of D , we measure the capillary force by differential weighting by an high precision balance.

Figures 3 and 4 give some examples of experimental and theoretical capillary forces at the same conditions. The graphs correspond to four configurations of the capillary doublet. We see that the capillary

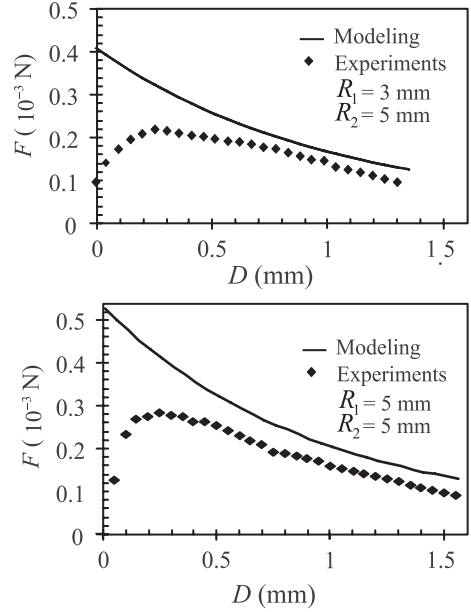


Figure 3. Experimental and theoretical capillary forces for different sizes of capillary doublets and for liquid bridges such as $V = 3 \text{ mm}^3$.

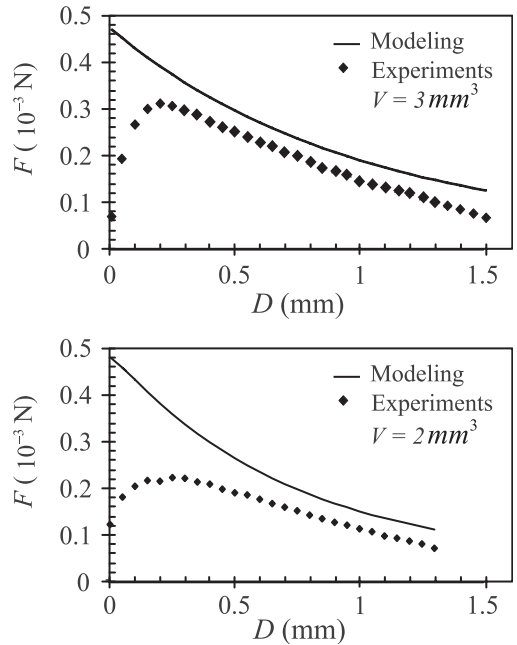


Figure 4. Experimental and theoretical capillary forces for different volumes of liquid bridge and for $R_1 = 4 \text{ mm}$ and $R_2 = 5 \text{ mm}$.

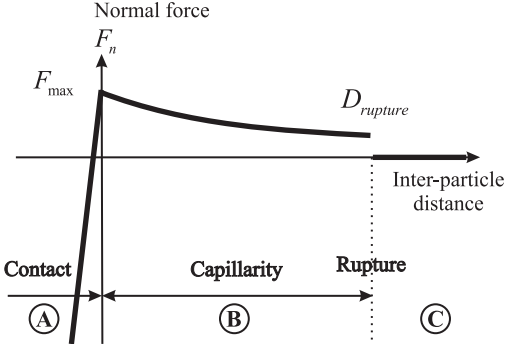


Figure 5. Illustration of the local force law of capillary type for a given volume of liquid bridge.

force decreases as a function of inter-particle distances (Fig. 3, 4), and, for a same inter-particle distance, the capillary force increases with the volume of the liquid bridge (Fig. 4). All the results show a quite good agreement between experiments and the model, except at low inter-particle distances where the setting up of the liquid bridge disturbs the measure of the capillary force. Our theoretical relation of capillary force seems thus acceptable in view of these experiments. The effect of gravity is not taken into account in the modeling of the capillary force (2). If we take into account the weight of the liquid bridges in experiments, then the capillary force is overestimated (from $2.10^{-5} N$ to $3.10^{-5} N$) by the model. Concerning the macroscopic scale, the effect of gravity on the liquid bridges is still an open issue because of the spatial distribution of liquid bridges in the whole granular material.

The capillary force decreases for increasing inter-particle distance up to the rupture of the liquid bridge. For monodisperse case, Lian et al. (1993) proposed a theoretical rupture criterion of the liquid bridge that gives the rupture distance as a function of the liquid bridge volume and of the contact angle:

$$D_{rupture} = (1 + 0.5\theta) V^{1/3} \quad (4)$$

Experiments at the local scale show that this criterion remains appropriate also for polydisperse case.

On the basis of these considerations, we propose a local interaction law of capillary type that gives the normal force between grains as function of the inter-particle distance and of the liquid bridge volume. This law takes into account the contact between grains, the capillary cohesion and the rupture (Fig. 5).

3 MACROSCOPIC SCALE: SIMULATIONS

The above force law is implemented in a numerical code based on a ‘Discrete Element Method’

Table 1. Input parameters for DEM simulation of humid granular assemblies.

Parameters	Values
Granular distribution	0.4 10
(radius in <i>mm</i> - fraction %)	0.45 20
	0.5 20
	0.55 20
	0.6 20
	0.65 10
Density of particles (kg/m^3)	2500
Contact angle θ (<i>rad</i>)	0
Surface tension σ ($N.m^{-1}$)	73.10^{-3}
Normal stiffness (contact)	10^6
Inter-particle friction coefficient	0.3
Time increment (<i>s</i>)	10^{-6}

(Cundall & Strack 1979). The code is under development, and so far, we are able to compute tests on 3D polydisperse granular materials with cohesive interactions. In this study, we present an application to the case of cohesion by capillary forces for different water contents (mass of water divided by the mass of grains). Contact and friction between grains are also taken into account in the simulations. Moreover, we need a way to connect the macroscopic water content to the volumes of liquid bridges at the local scale. To this end, we use an empirical criterion based on the sizes of the doublets of grains that allows us to distribute the macroscopic volume of water in the granular assemblies.

Simulations of radial compression are done on a cylindrical granular assemblies. The granular assemblies is composed of 8000 polydisperse grains for a diameter of the sample of 25 *mm* and a height of 17 *mm*. The porosity of the sample is $n = 0.38$. Parameters used for simulations and the granular distribution in terms of numbers of grains are given in Table 1. For the simulations, we set the gravity to zero in order to single out only the effect of capillarity. Compressions are realized at a constant speed of 2.5 *mm/s* until a displacement of 2 *mm* of the upper plate, which corresponds to 8% in strain.

Figure 6 illustrates three snapshots of a test. The sample keeps its mechanical integrity due to the presence of capillary cohesion.

The Figure 7 shows the evolution of the compressive force as a function of the displacement of the upper plate for three water contents: $w = 1\%$, $w = 3\%$ and $w = 6\%$. For displacements of the upper plate lower than 0.15 *mm*, the three curves are identical. In this range, only contacts between grains (compressive forces) support the compressive action of the plate (zone A in Fig. 5). For higher displacements, the distances between grains become larger and tensile forces are mobilized. Then, we can observe the effect of capillary forces (zone B in Fig. 5). For a same displacement

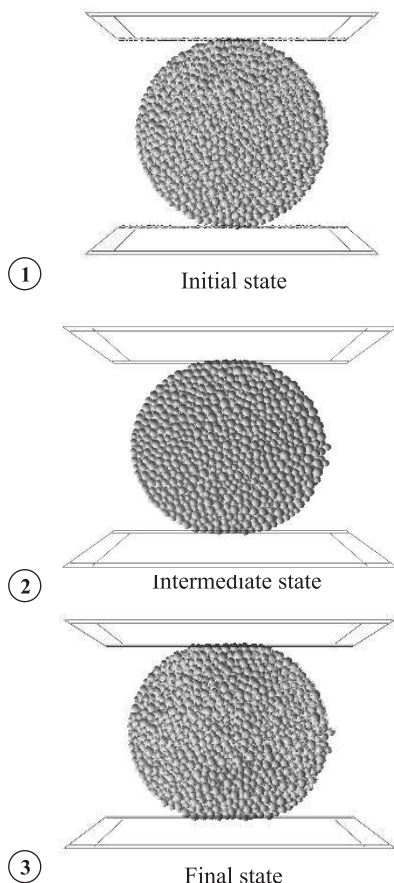


Figure 6. Simulation of the radial compression of a granular assembly composed of 8000 polydisperse grains for a 3% water content. Illustrations done with mgpost (Richefeu 2004).

of the upper plate, the compressive force increases with the water content. At the local scale, for a same inter-particle distance, the capillary force increases with the volume of the liquid bridge (Fig. 4). This agrees with the evolution of the macroscopic compressive force. These results demonstrate the influence of water content on the macroscopic behavior of granular assemblies.

Numerical simulation of cohesive agglomerates is in an active phase of development. Behavior of agglomerates composed of cohesive particles have been reported by several authors (Lian et al. 1998; Thornton et al. 2004; Delenne et al. 2004).

4 CONCLUSIONS

In this paper, we have studied the capillary cohesion in polydisperse granular materials.

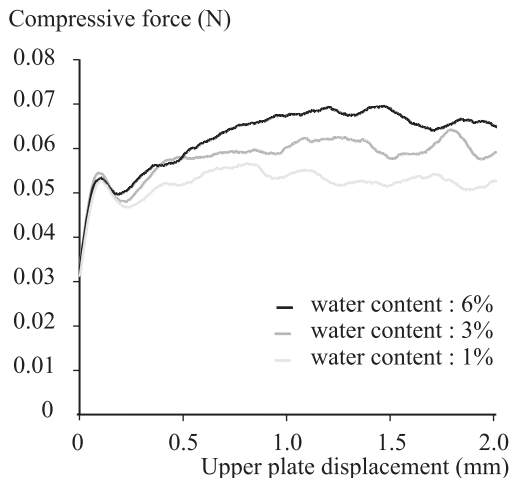


Figure 7. Evolution of the compressive force with the displacement of the upper plate during the radial compression of humid polydisperse granular assemblies.

We have presented an explicit relation describing the capillary force between grains of different sizes as a function of the characteristics of the material. The theoretical model was validated by experiments at the local scale.

Taking into account contact, capillary cohesion and rupture, a local force law of capillary type was proposed and implemented in a numerical code based on DEM.

Radial compressive tests were simulated in the case of humid polydisperse granular assemblies. The results show the effect of local cohesion, due to water content, on the macroscopic behavior of granular materials.

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