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# About “Flow of wet granular materials: a numerical study”.

## Response to a Comment by B. Chareyre.

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(Dated: July 8, 2017)

In his Comment on our 2015 paper [1], Bruno Chareyre criticizes, as inaccurate, the simple approach we adopted to explain the strong enhancement of the quasistatic shear strength of the material caused by capillary cohesion. He also observes that a similar form of the “effective stress” approach, accounting for the capillary shear stress, which we neglected, results in a quantitatively correct prediction of this yield stress. We agree with these remarks, which we deem quite relevant and valuable. We nevertheless point out that the initial approximation, despite  $\sim 25\%$  errors on shear strength in the worst cases, provides a convenient estimate of the Mohr-Coulomb cohesion of the material, which is directly related to the coordination number. We argue that the effective stress assumption, despite its surprising success in the range of states explored in [1], is bound to fail in strongly cohesion-dominated material states.

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In our 2015 Physical Review E paper [1] we investigate, by discrete numerical simulations, the constitutive laws of wet spherical grains in steady shear flow, in relation to micromorphology and micromechanics. Assemblies of beads of diameter  $a$ , made of a material with mass density  $\rho$ , are subjected to a slow shear flow, with controlled shear rate  $\dot{\gamma} = \frac{\partial v_1}{\partial x_2}$  and normal stress  $\sigma_{22}$ . (index 1 labelling the flow direction and index 2 the velocity gradient direction). We characterize the material behavior through the apparent friction coefficient,  $\mu^*$ , conventionally defined, as in cohesionless materials, as the ratio of the shear stress to the normal stress:  $\mu^* = \sigma_{12}/\sigma_{22}$ . One major control parameter is the reduced pressure  $P^*$  comparing the controlled normal stress  $\sigma_{22}$  to the capillary attractive force  $F_0$  between contacting grains:  $P^* = a^2 \sigma_{22}/F_0$ . Together with inertial number  $I = \dot{\gamma} a \sqrt{\rho/\sigma_{22}}$ , reduced pressure  $P^*$  determines the internal state of the material in steady uniform shear flow.

The issue discussed in the Comment is the definition of effective stresses  $\underline{\sigma}^{\text{eff}}$ , such that, in the quasistatic limit of  $I \rightarrow 0$ , the flow condition (yield criterion) takes the form  $\sigma_{12}^{\text{eff}} = \mu_0^{*\infty} \sigma_{22}^{\text{eff}}$ , with the static internal friction coefficient  $\mu_0^{*\infty}$  of the dry material (corresponding to the limits of  $P^* \rightarrow \infty$  and  $I \rightarrow 0$ ).

In our paper, we argue that the effect of capillary forces, contributing  $\underline{\sigma}^{\text{cap}}$  to the total stress, could be likened to a shift in stresses transmitted through the contact network, and we adopt these shifted stress values as effective stresses. We choose nevertheless to ignore the shift in shear stress, and indeed our simplifying approach amounts to writing  $\sigma_{12}^{\text{eff}} = \sigma_{12}$  and  $\sigma_{22}^{\text{eff}} = \sigma_{22} - \sigma_{22}^{\text{cap}}$ . This omission is criticized by Chareyre in his Comment,

as entailing poorer predictions of shear strength. He points out that on accounting for all terms of the capillary stresses, the quasistatic criterion written as in (his) Eq. 1 very closely fits all simulation data points (Fig. 1) pertaining to homogeneous quasistatic flows. As, on ignoring  $\sigma_{12}^{\text{cap}}$ , we obtain a relative error growing to 25% at small  $P^*$ , he therefore concludes that we are unduly pessimistic in our assessment of the performance of shear strength predictions based on the effective stress approach.

We find this conclusion well founded for the main data series of Ref. [1], we agree that the success of the assumption that the contact stresses (defined as  $\underline{\sigma}^{\text{cont}} = \underline{\sigma} - \underline{\sigma}^{\text{cap}}$ ) are effective stresses is remarkable, and that this observation nicely agrees with other results [2]. Thus, we regard the Comment as very relevant and interesting.

The perspectives of our work [1] (see also [3]), in which many other aspects of wet granular material rheology are addressed, were actually slightly different. Our main motivation on invoking effective stress ideas was to provide a physical explanation for the strong increase of friction coefficient  $\mu_0^*$ , the quasistatic limit of  $\mu^*$ , as  $P^*$  decreases through the investigated range. In this respect, the simplified approach ignoring  $\sigma_{12}^{\text{cap}}$  proves quite successful, as it provides a semi-quantitative prediction of the shear strength with simple means. As an additional advantage, it justifies the existence of a cohesion in the sense of Mohr-Coulomb, with a value that relates in satisfactory approximation to  $F_0$ , solid fraction  $\Phi$  and coordination number  $z$  as

$$c = \frac{z\Phi\mu_0^{*\infty}F_0}{\pi a^2}. \quad (1)$$

This lends itself to interesting comparisons with the literature [4, 5] and correctly assesses cohesive contributions to strength for  $P^* \geq 1$ . Using the full contribution of capillary forces to the stresses is more accurate, but  $\sigma_{12}^{\text{cap}}$  is not as easily related to the simplest state variables  $\Phi$  and  $z$ . In recent simulations with a slightly different sys-

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tem [6], we also observed  $\sigma_{12}^{\text{cap}}$  to vary significantly with  $P^*$ .

A more complete exploration of the range of validity of postulate  $\underline{\underline{\sigma}}^{\text{eff}} = \underline{\underline{\sigma}}^{\text{cont}}$  is still needed, as its physical origin remains mysterious. The basic objections put forth in [1], about the microstructure differences induced by cohesion, should bear some relevance. Cohesive systems might form stable structures with very low densities [3] (e.g.,  $\Phi = 0.25$ ) inaccessible to cohesionless ones, in which case the comparison with dry materials subject to the effective stress makes no sense. Such configurations are however

associated with low  $P^*$  values for which homogeneous shear flow were not observed. Similar numerical simulations of wet bead assemblies in shear flow were recently carried out in our group [6], with a different value of the intergranular friction coefficient,  $\mu = 0.09$ , motivated by quantitative comparisons with an experimental system. The effective stress postulate (accounting for  $\sigma_{12}^{\text{cap}}$ ) is observed to predict the shear resistance with an accuracy better than 5%, except for  $P^* < 1$  and small liquid contents ( $V_m < 10^{-4}a^3$  with the notations of [1]), in which case the error grows to order 10%.

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