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Impact of the fines content on stress fluctuations in bi-disperse granular mixtures during triaxial tests

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Abstract. In this experimental study, the influence of fines content and specimen preparation method on the mechanical behavior of granular mixtures have been explored by studying stress fluctuations that occur when the mixtures are subjected to drained triaxial tests. The magnitude and distribution of stress fluctuations are related to the changes in the microstructure of the ensemble. Bi-disperse granular mixtures of glass beads with a size ratio of 8.8, over the entire range of fines content F_c (0% to 100%) were considered. The specimen were prepared using two standard specimen preparation techniques, dry deposition and moist tamping to recreate two distinct microstructures. It is found that in the under-filled regime where the stress transmission is mainly governed by the coarse particles, a significant increase in the magnitude of fluctuations is observed as the fines content, F_c, increases, and on the contrary in the overfilled regime, where the load bearing structures are mainly made up of fines, fluctuations are found to decrease with further increase in F_C which suggests that larger the interplay between coarse and fine particles, larger the fluctuations. Further investigation of these fluctuations in the context of critical avalanche dynamics or Self Organized Criticality (SOC) is performed.

1 Introduction

When sheared, the mechanical response of granular materials is governed by different mechanisms such as the contact interaction between the particles and the geometry of their contact network. The dynamics of the contact network involves contact slips by either translation or rotation and also loss and gain of contacts. This latter mechanism has been shown to correlate with the stress fluctuations in the material response [1]. In this context, we investigate the relationship between changes in the microstructure and the distribution of stress fluctuations by considering a model granular material made of glass beads with varying fines content. Changing the fines content may be seen as a way to control the size of the energy released during such rearrangements. With this objective, bi-disperse granular mixtures of glass beads with a size ratio, equal to D_{50}/d_{50}, of 8.8 (coarse grains $D_{50} \sim 3.7$ mm - passing through 4 mm sieve and retained by 3.35 mm; non plastic fines have a $d_{50} \sim 0.41$ mm - passing through 0.5 mm and retained by 0.315 mm sieves) have been considered and subjected to drained triaxial shearing. Two different specimen preparation methods were chosen, the dry deposition and the moist tamping technique [2]. For the dry deposition method, mixtures have been prepared with fines content, F_c ($F_c = \frac{m_f}{m_c+m_f}$ with m_f being the mass of fines and m_c being the mass of the coarse fraction of the mixture) ranging from 0% to 100% while for the moist tamping method, F_c ranges from 10% to 50%. The specimens were prepared at a relative density of 90% by experimentally determining the e_{min} and e_{max} for each F_c presented in Figure 1. For moist tamped specimen, ~ 5% of water (in terms of the mass of the specimen) was added during specimen preparation. Based on the discrete element analyses of [3], the minimum void ratio in Figure 1 provides a threshold F_c value that categorizes the material into an under-filled regime, where the mechanical response is primarily governed by the contact network of coarse particles, and an overfilled regime, in which the fines dictate the macroscopic behavior of the system. With this knowledge, it is hypothesized that this transition should also reflect on stress fluctuations.

2 Results

Drained triaxial tests were performed on the mixtures under saturated conditions, with the B values (Skempton's co-efficient) for each test being at least 0.96. The specimen were of dimension 140 mm by height and 70 mm diameter. All the experiments have been performed at 100 kPa of effective confining stress and a strain rate of 1% per minute. The stress-strain response of the mixtures at different fines content and specimen preparation meth-

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ods have been presented in Figure 2 and Figure 3. The peak deviatoric stress obtained from the dry deposition method is always higher than that of the moist tamping method for all F_c values which is consistent with observations from previous studies and is a direct consequence of the distinct microstructures obtained due to the specimen preparation method. Moist tamping method promotes the formation of more heterogeneous microstructures with macro-pores that are known to be less stable than the more homogeneous pore distribution found in the dry deposition method [2]. Also at 0%, and for F_c values greater than 30%, there is a strong strain softening behavior observed which is much weaker for F_c values in the under-filled regime. A similar remark can be made for the moist-tamped specimens as evident from Figure 3 that in the overfilled regime the strain softening becomes more apparent than in the under-filled regime. The different post-peak softening rates observed for the different preparation method can be interpreted from the bifurcation theory as being indicative of different strain localization patterns [4]. Visual inspection of Figures 2 and 3 further reveals large fluctuations in the deviatoric stresses for the under-filled regime beyond which the fluctuations subside in the over-filled regime even though all the specimen have been prepared at the same density. Moreover, the fluctuations exhibit similarity across different observation windows. The origin of these stress fluctuations remains difficult to pinpoint. However, some plausible mechanisms can be considered. In the under-filled regime, the increase in fluctuations with the addition of fines may arise from changes in the contact mechanics, particularly stick-slip events, or from mesoscale rearrangements associated with energy release during the collapse of force chains. It is also possible that a combination of both mechanisms contributes to the observed behavior. The size of the fluctuations might also be influenced by the system size (number of particles), since we expect similar level of fluctuations at 0% and 100% F_c [3].

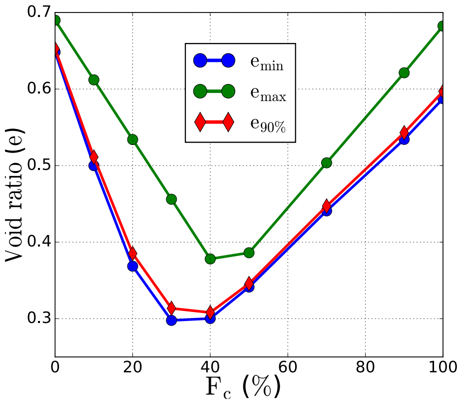

Figure 1. Evolution of void ratios as a function of fines content, F_c

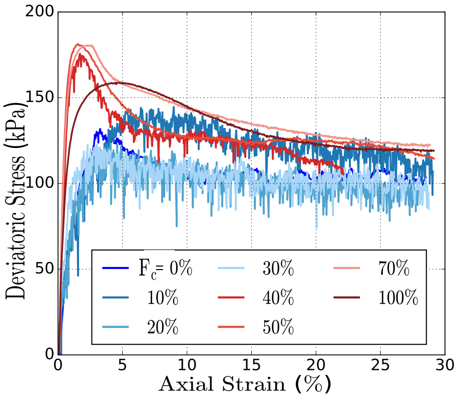

Figure 2. Drained shear behavior of granular mixtures at different fines content for specimen prepared using dry deposition

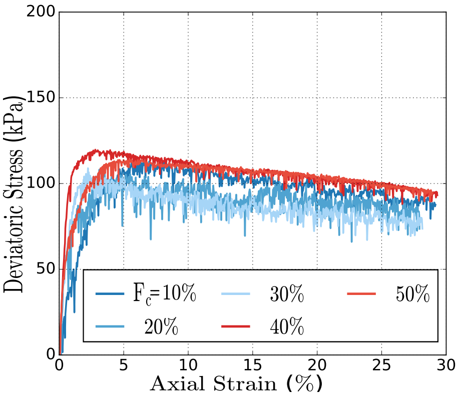

Figure 3. Drained shear response for moist tamped specimen

2.1 Stress fluctuations

Stress fluctuations are analyzed by identifying the local stress peaks and drops of the deviatoric stress curve as shown in Figure 4 with the peaks indicated by triangles(t^-) and stress drop (t^+) by circles with the magnitude of fluctuations taken as, Δq = q(t^-) - q(t^+). In Figure 5, the largest magnitude of stress fluctuation, Δq_{max} (obtained from the cumulative distribution of Δq values) has been plotted as a function of F_c for both specimen preparation methods. A sharp increase in Δq_{max} value is observed as the system moves into the under-filled regime from 0% F_c and a clear peak is identified for a F_c value of 20% beyond which the value begins to drop as the system moves out of the under-filled regime and into the over-filled regime. From a mesocopic point of view, the following conjecture is proposed. Numerical findings of [3] indicate that in the under-filled conditions, the skeleton void ratio increases with addition of fines and reaches a maximum at the threshold fines content. As the skeleton void ratio increases, the load bearing force chains become sparse and hence when these metastable structures do collapse, they produce more significant drops in the deviatoric stress. As we enter the overfilled regime, the skeleton void ratio begins to decrease resulting in an increase in the population of the forces chains which consequently leads to the observed reduction in the magnitude of stress fluctu-

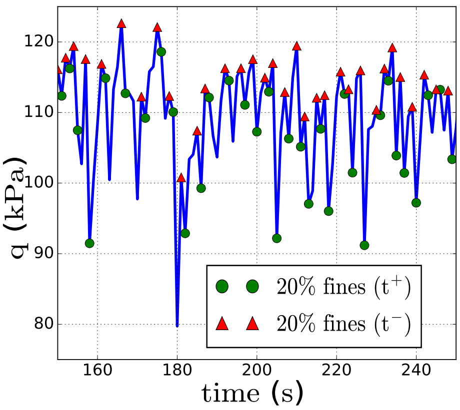

Figure 4. Local peaks and drops in deviatoric stress at critical state.

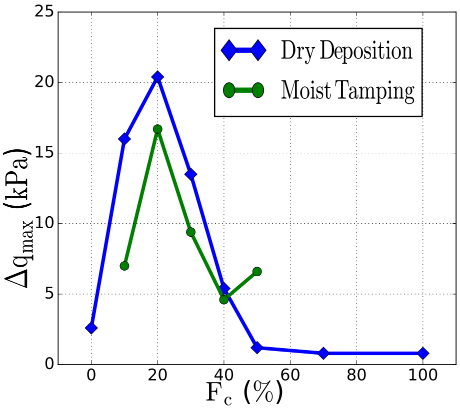

Figure 5. Largest magnitude of stress fluctuation observed for different fines content at critical state ($\epsilon > 15\%$) .

ations. Stick-slip mechanisms at grain contacts may also contribute to the collapse of force chains but remains difficult to quantify at this stage. The distribution of stress fluctuations, taken across the entire duration of deformations, are presented in Figure 6 and 7 for dry deposition and moist-tamping methods respectively. The fluctuations are found to be better described by an exponential distribution than a power law and hence can be imagined to be arising out of a Poisson-like process. This then suggests that the size of a given fluctuation, or in other words the size of the mesoscale particle rearrangements, at any given instant may not necessarily be correlated to the size of the fluctuation at a previous instant [1].

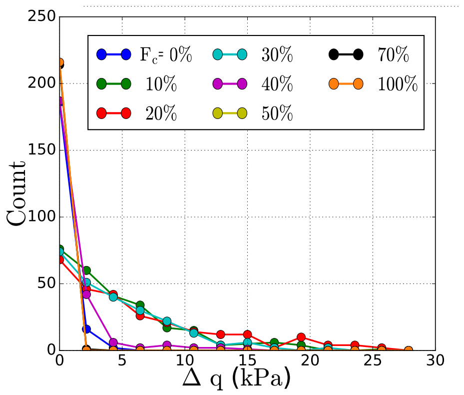

Figure 6. Distribution of stress fluctuations for the dry deposition method.

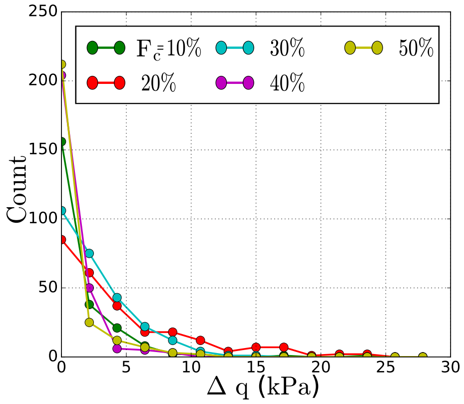

Figure 7. Distribution of stress fluctuations for the moist tamping method.

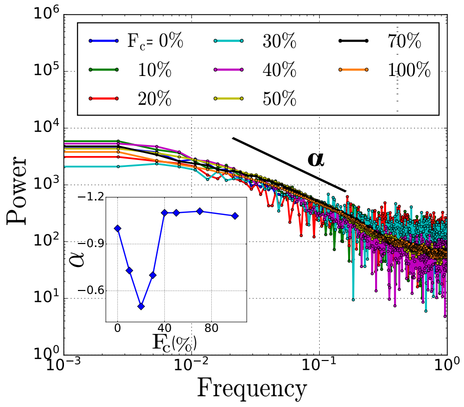

Figure 8. Power spectrum of stress fluctuations - Dry deposition

To probe the nature of these fluctuations further and to interpret the observations within the purview of self organized criticality, the power spectrum of time signals, presented in Figure 2 and 3, were obtained from the Fast Fourier transforms and plotted as a function of the frequency for all the tests cases in Figure 8 and 9. In accordance with previous studies [1], a power-law relationship of the form $Power \propto (Frequency)^{\alpha}$ is recognized together with a cut-off at lower frequencies that is imposed by the total duration of the the experiment and a high frequency cut-off that is a signature of data acquisition frequency. It is to be noted that this relationship is qualitatively different to the noise coming from the data acquisition system which is characterized by a flat power spectral density. Moreover, such noise would be expected to induce comparable levels of fluctuation irrespective of the fines content. However, on the contrary, a significant increase in stress fluctuations is observed, with the most pronounced fluctuation occurring at 20% F_c. In the inset of the figures, the evolution of α is plotted as a function of F_c values and interestingly, we observe similar trends as was observed in

Figure 5, with α value decreasing as we enter the underfilled regime, has a minimum at 20% F_c and increases as the system moves to the overfilled regime. Regardless of the different stress-strain responses, a comparable power-law exponent is obtained for different F_c values and specimen preparation methods hinting at criticality that is independent of the initial condition of the experiments.

Thus, it can be concluded that in bidisperse granular mixtures, the transition in mechanical behavior from a coarse particle dominated to a fine particle dominated regime can also be identified through the fluctuations observed in deviatoric stresses. The origin of these fluctuations remains difficult to pinpoint and is likely influenced by mechanisms operating across multiple scales, the contact scale, mesoscale, and also at the system scale. Preliminary findings suggest that the introduction of fines may allow the system to modulate the magnitude of energy released through stress fluctuations. This observation merits further investigation through second-order work computations and non-invasive techniques such as bender element testing or acoustic emission monitoring. Similar analysis using discrete element method (DEM) simulations is currently underway and will be presented in forthcoming publications.

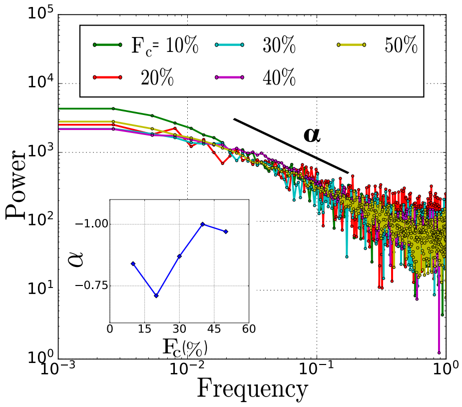

Figure 9. Power spectrum of stress fluctuations - Moist tamping

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