Granular Jamming as Controllable Stiffness Mechanism for Medical Devices

L. Blanc, A. Pol, B. François, A. Delchambre, P. Lambert, and F. Gabrieli

Abstract Endoscopic medical devices require high bending flexibility to navigate through tortuous channels while exhibiting some stiffness to exert force on tissues. The granular jamming is a solution which can be implemented at the tip or along the body of these devices to control their stiffness. In this work, the stiffness of sphere packings is studied experimentally and modeled by Discrete Element Method (DEM). The secant stiffness, at a medium level of strain, is evaluated by means of special vacuum assisted triaxial compression tests using polydisperse glass beads as granular material. A cycling method is performed during the experimental procedure to ensure the repeatability of the measurements by eliminating the initial experimental conditions and to be compared to the DEM results. The model has been calibrated by fitting the experimental curves and varying the contact stiffness of the particles, the contact friction angle, the grain size distribution and the confining stress. This numerical tool is used for forecasting the behavior outside the experimental conditions. Among all parameters, the pressure difference shows the largest effect on the stiffness change and can therefore be used as the stimulus for future controllable stiffness medical devices.

Keywords Granular jamming · Triaxial compression · DEM model · Stiffness · Medical device

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1 Introduction

Predicting the stiffness of granular media and identifying the factors that influence its value are relevant challenges in geomechanics, especially to evaluate its mechanical behavior in conditions far from failure.

Many authors studied the stiffness degradation with strain, which is particularly significant for cyclic and dynamic geomechanical problems but also for structure interactions problems [1]. The non-linear stress-strain behavior, the influence of the confining stress level and the dependencies from the stress path [2–4] are only some of the aspects which complicate the estimate of the stiffness of these materials.

Other theoretical, numerical and experimental studies, mainly with mono-size regular particles, also from the field of mechanical and industrial engineering, were devoted to the prediction of the elastic stiffness moduli [5–7]. These works showed how the initial stiffness of such materials is strongly related to the contact physical parameters like the elastic contact stiffness and to geometrical parameters such as the particle shape, the coordination number or the porosity of the packing.

From an applicative point of view, varying the stiffness by the stress level in granular materials is a very interesting way to develop smart controllable stiffness devices like jamming-based grippers [8]. In this case, the transition between a soft state of the gripper, useful to conform with the object geometry during the gripping phase, and a stiffer one, to hold the object against gravity, is controlled by imposing air or fluid suction (which is equivalent to a confining stress) to a balloon filled with granular material. Particularly, in endoluminal surgery and biomedical engineering, the development of new endoscopic tools and catheters could benefit from adaptive stiffness principles [9]. Indeed, a flexible state is required to adapt to tortuous paths of the human body and avoid painful contact force with the patient tissues, while a stiffer mode is needed to transmit force and for accurate positioning.

In geomechanics, stiffness of soils is routinely measured in the laboratory from quasi-static (e.g. triaxial tests) and dynamic tests (e.g. resonant column). Depending on the range of shear strain of interest, the conventional test apparatus like the triaxial cell can be equipped with high-resolution strain transducers, bender elements or ultrasonic sensors in order to appreciate the small-strain stiffness behavior. A reference stiffness evaluated in triaxial compression tests after loading-unloading cycles is shown to be sufficient in this work for a medium strain regime of applications (strain $\epsilon_z < 10^{-2}$). This work is focusing on the identification of the factors affecting the stiffness of a packing of glass spherical particles, towards the construction of rationales for improved design of granular jamming-based endoscopic medical devices. These experimental triaxial tests were also reproduced with discrete element simulations with the aim to understand the micromechanical aspects such as the influence of the contact stiffness and the confinement conditions. In the future, this numerical approach will be extended to model more complex conditions for other applications.

2 Experimental Triaxial Compression Tests

The triaxial compression test is used in geomechanics to characterize soils and granular materials under a defined confinement [10]. Conventional axisymmetric triaxial tests permit to measure the axial stress-strain properties (e.g. the stiffness and the ultimate stress) under monotonic deviatoric loading starting from an isotropic stress state which is obtained and conserved with the application of an external pressure or an equivalent negative internal pressure. The deviatoric stress q is here defined as the difference between the axial stress and the applied confining pressure. This test allows for characterizing the soil behavior under confining stresses close to the field conditions. For this work, vacuumed samples have been tested in place of the conventional water pressurized samples while a standard loading machine (*LS1, Lloyd*) is used for performing the axial compression phase. Vacuuming the samples instead of applying a confining pressure by pressurized water limits the pressure difference to the atmospheric pressure only, but helps for working with dry samples and for avoiding friction from the triaxial cell. Here, the vacuum level in the sample is controlled in order to set the confining stress and to study its effect on the stiffness of the granular material.

The samples are cylindrical (with a diameter of 36.9 mm $\pm$ 0.7 mm and a height of 74.6 mm $\pm$ 1.3 mm) for ensuring axis-symmetrical confining pressure conditions. A fixed mass (125 g) of granular material is poured in a latex membrane (70 μm thick). The granular materials used in these experiments are glass beads with a diameter ranging from 750 μm to 1000 μm and with a roundness higher than 95%. A constant pressure is applied to the sample by keeping the vacuum pump equipped with a vacuum meter working during the entire duration of the test. The compression speed of the tests has been set to 5 mm/min (giving an average of $1.1 \cdot 10^{-3}$ s^{-1} as strain rate) ensuring therefore quasi-static conditions.

Since the initial conditions (sample preparation, initial configuration, mechanical contacting) influence the initial stiffness, a fixed specific preconditioning procedure is applied to the triaxial compression samples. Successive cycles of loading and unloading down to the isotropic stress state are applied after an initial loading of 2 mm as illustrated in Fig. 1a. This loading-unloading cycling method was also applied in the study of granular packings by Athanassiadis et al. [11] and proved to give more repeatable compression curves after the cycling procedure. For each confining pressure, three specimens have been tested.

A reference secant Young modulus E^*_{50} is calculated in the linear region of the loading cycles between 25% and 50% of the ultimate stress $q_{\max}$ (Fig. 1b). This reference Young modulus increases during the first cycles and stabilizes after approximately 10 cycles (as seen for example in Fig. 1c for a test performed with a pressure difference of 75 kPa). Therefore, 10 loading-unloading cycles are used in this experimental study. The last loading is considered as the new compression test starting after the preconditioning phase which is used to improve the experimental repeatability.

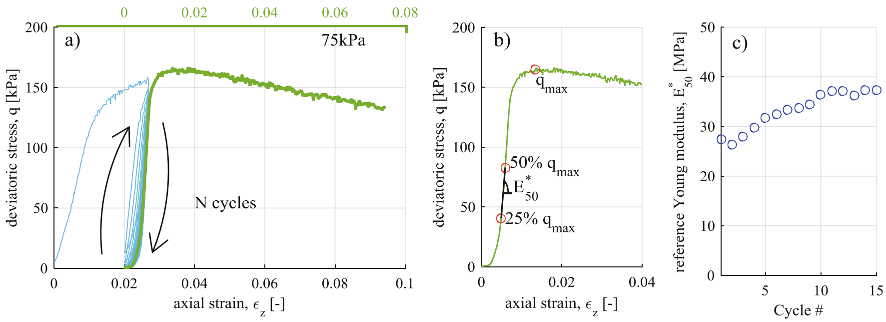

Fig. 1 (**a**) Multiple loading-unloading cycles precede the monotonic compression test used for the stiffness evaluation (the green line). (**b**) The reference Young modulus is then evaluated between 25% and 50% of the ultimate deviatoric stress $q_{\max}$. (**c**) The reference Young modulus value is stable after 10 cycles

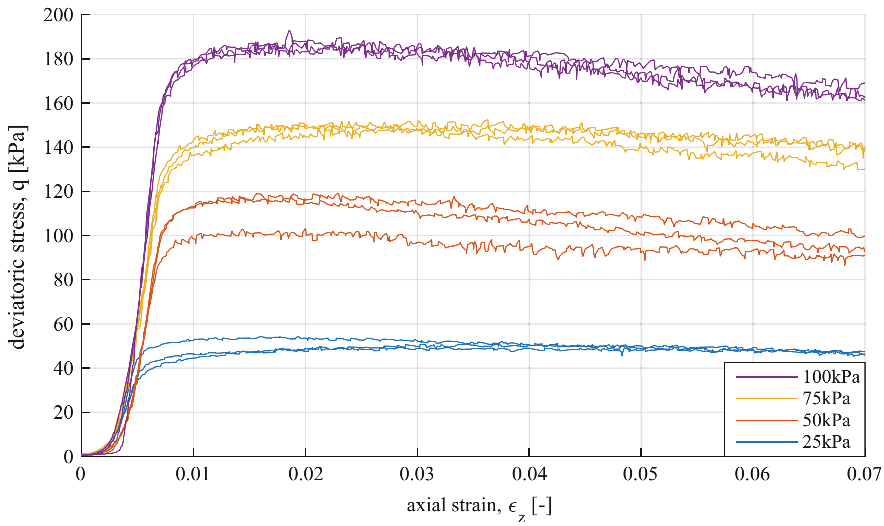

Fig. 2 Monotonic stress-strain curves obtained for the different confining pressures after the cycling method (three repetitions are represented)

The different confining pressures give the stress-strain curves illustrated in Fig. 2. The ultimate stress $q_{\max}$ and the reference Young modulus in compression E^*_{50} are increasing with the pressure difference. In the following, the strain is considered to start from 0 after the preconditioning of the ten loading-unloading cycles.

3 Calibration of the DEM Simulations with the Experiments

The Discrete Element Method (DEM) has been proved to be a powerful method to investigate the collective behavior of packing of spheres in static as well as in dynamic conditions, from loading problems to granular flows simulations.

In our tests, a Hertzian contact model is used and represents, with some hypotheses, the analytical solution of the contact problem between two spherical elastic surfaces. In this model, the normal contact force non-linearly depends on the indentation at the contact (i.e. the overlap in soft contact approaches like the DEM) giving a better agreement of the overall macroscopic elastic properties of the assembly than with a simple linear elastic law [12]. The tangential contact forces instead are handled with a classical Mindlin model [13].

To model the experimental triaxial tests, cubic triaxial tests are performed in a periodic cell with approximately 3000 particles. The open-source code YADE [14] is used to perform these 3D DEM simulations.

The calibration of the model parameters was achieved through a trial-and-error approach simulating several triaxial tests at the same confining pressures as the experimental ones and varying the micromechanical parameters in a reasonable range. The following parameters have been considered and calibrated (here reported with their best-fitting value): the contact Young modulus $E_m = 1.84$ GPa, the contact Poisson's ratio $\nu_m = 0.25$, the inter-particle friction angle $\phi_m = 28^{\circ}$, the rolling stiffness coefficient $k_r = 0.01$ and the rolling friction coefficient $\eta_p = 0.05$.

The DEM simulations have been validated by comparing the deviatoric stress-strain curves with the experimental results. As shown in Fig. 3a, the results of the DEM model are promising for modeling the behavior of granular packing under various confining pressures. The initial slope is higher in the model than in the experimental results. This may be explained by the relaxation of the samples in the experimental work for low deviatoric stress, resulting in a lower initial slope after the loading-unloading cycles. Therefore, the starting point of DEM results

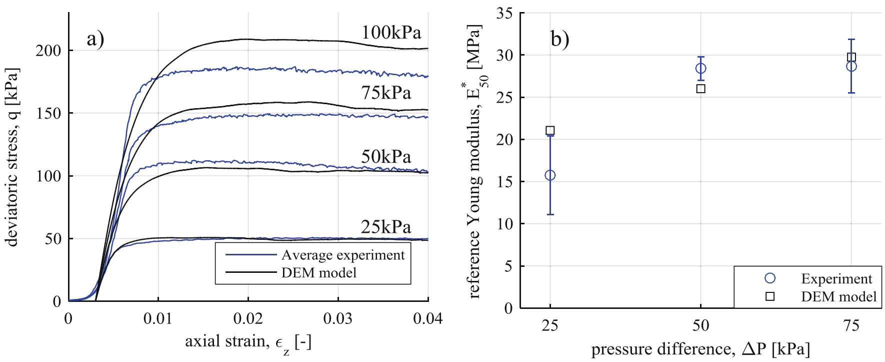

Fig. 3 Results of the validation phase for: (**a**) the deviatoric stress q as function of the strain ϵ_z and (**b**) the trends of the reference Young modulus with confining pressure

has been slightly shifted for the comparison. The main trends fairly agree and the ultimate stresses $q_{\max}$ are close in the experiments and in the model for the different confining pressures. The differences between the experimental and numerical curves for the sample at 100 kPa of vacuum pressure are probably due to the experimental limitations in achieving such low pressure values. For this reason, the corresponding reference Young modulus values were not depicted.

In Fig. 3b, the reference Young moduli E_{50}^{*} obtained from experimental curves are compared with those obtained by DEM. As it can be observed, the experimental results are repetitive, which confirms the interest of the cycling procedure used for the experimental tests. The DEM model provides reference Young moduli close in value to the experimental data and $q - \epsilon_z$ curves which follow the same trend as the experimental results. Building on the satisfactory agreement between DEM model and experiments, the DEM model will be used in the next section to achieve a sensitivity analysis.

4 Sensitivity Analysis of the Parameters in DEM Simulations

In order to investigate the role of the micromechanical parameters on the macroscopic elastic response, a sensitivity analysis is performed. Moreover, the influence of the particle size distribution of the packing and of the confining pressure is also analyzed. In the following, the results will be reported with reference to the evolution of the secant modulus E_{sec} (defined in this work as the local slope of the deviatoric stress-axial strain $q - \epsilon_z$ curve) and to the reference Young modulus E_{50}^{*} defined previously.

First, the influence of the elastic modulus at the contact E_m was investigated. Its value was varied from 0.63 to 63 GPa to mimic a wide set of materials that might be used for such medical applications (as hard rubber, plastic polymers or glass). It is important to highlight that generally the E_m value differs from the Young modulus provided by the manufacturer. Indeed, the reduction in effective contact stiffness due to the asperities on the particles surface has to be considered [15]. Moreover, for the medium strain range of our triaxial tests, the use of a reduced value has been proved to provide a better result in the evaluation of the stress-strain curves.

The macroscopic elastic modulus of the packing E_{50}^{*} increases with E_m (see Fig. 4a) according to a power law with an exponent equal to 0.64 which is very close to 2/3 as predicted for initial stiffness by several models [16]. The evolution of the macroscopic elastic modulus E_{sec} as a function of the axial strain is shown in Fig. 4b. It is noticeable that a different micromechanical Young modulus affects the macroscopic stiffness values only for a narrow level of strain before peak ($\epsilon_z < 5 \cdot 10^{-3}$).

For a chosen material (i.e. a fixed set of contact parameters), one might be interested to know if the mechanical response of the packing, and in turn of the medical device, can be changed varying the Particle Size Distribution (PSD) of the granular material. For this purpose, the PSD is here defined in a simplified

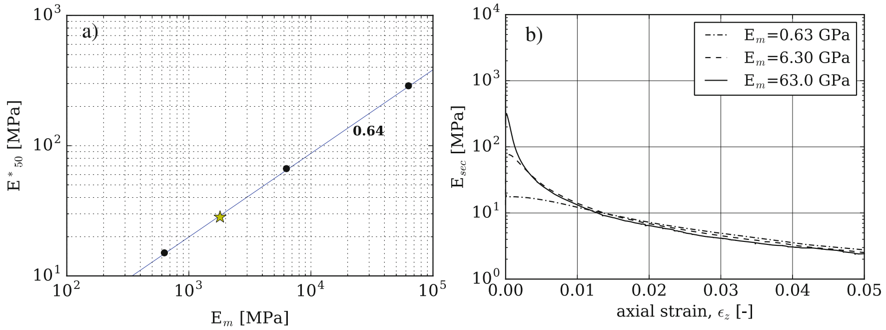

Fig. 4 (**a**) Dependence of the elastic modulus E^*_{50} on the micromechanical Young modulus E_m for 50 kPa of confinement stress and (**b**) evolution of the secant modulus E_{sec} with the axial strain level ϵ_z. The yellow star represents the experimental reference value E^*_{50} ($\Delta P = 50$ kPa)

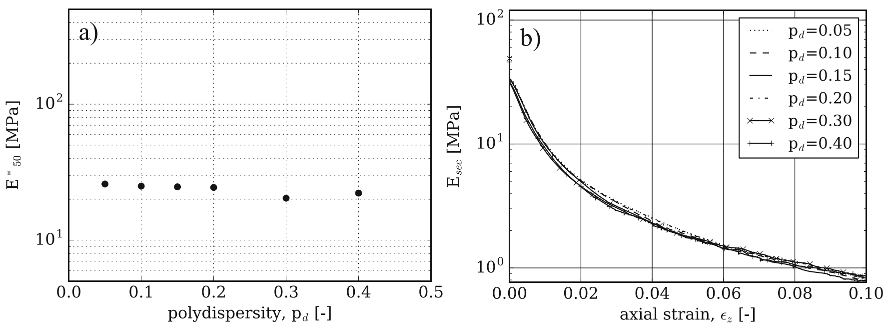

Fig. 5 (**a**) Dependence of the elastic modulus E^*_{50} on the polydispersity p_d and (**b**) evolution of the secant modulus E_{sec} with the axial strain level ϵ_z

way using two parameters: the mean diameter d and the polydispersity p_d. The polydispersity is defined as the dispersion of the grain size over its mean value, i.e. the biggest and the smallest particles have a diameter equal to $d \pm d \cdot p_d$. The results obtained for the range 0.05–0.40 of p_d are reported in Fig. 5. In this case a variation of the particle size distribution has a negligible effect on the stiffness for $p_d \leq 0.25$, whereas a slight reduction of E^*_{50} is observed for larger values (0.30–0.40). However, different PSD distributions should be considered in future studies to provide clear conclusions.

The other variable which controls the stiffness of the sample is the vacuum pressure (i.e. the confining stress). Many literature results of experimental tests and theoretical and numerical models report the existence of an exponential law which links the macroscopic elastic stiffness with the mean stress of the sample. The results obtained here from triaxial DEM simulations and experiments with spheres at different confining stresses confirm these results (see Fig. 6). Moreover, considering the evolution of the secant modulus the influence of the mean stress is relevant also for significant level of strain ($\epsilon_z \sim 2 \cdot 10^{-2}$).

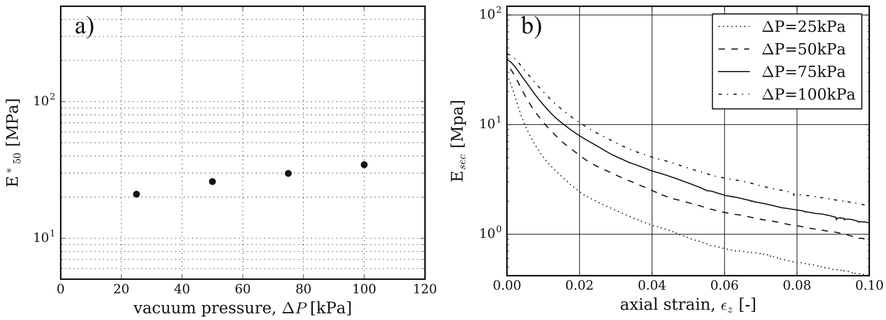

Fig. 6 (**a**) Dependence of the elastic modulus E^*_{50} on the vacuum pressure ΔP and (**b**) evolution of the secant modulus E_{sec} with the axial strain ε_z

5 Perspectives

In the future, bending tests should be considered in the evaluation of the material stiffness through material strength engineering models, taking into account geometries and loading conditions closer to the final application. The study of the flexural stiffness (*EI*) [17] can be performed for small-strain loading conditions such that a DEM model could be implemented based on the current results for the triaxial tests in order to validate the versatility of the method and the various solutions that can be implemented.

The DEM models could be used for testing the characteristics of the granular packings beyond the experimental conditions. It is possible to study the influence of a pressure difference larger than the atmospheric pressure. These models ease the study of some parameters (as the particles characteristics, the surrounding conditions, etc.) that are difficult to control for the experimental work. The use of different granular materials (shape, size and material of the particles) should complete the study of the stiffness for granular packing.

6 Conclusion

This work illustrates the strong influence of the confining pressure on the stiffness of granular packing, experimentally and by DEM simulations. The experiments have shown a good repeatability thanks to a specific procedure consisting in preconditioning the samples with ten loading-unloading cycles and vacuuming the samples instead of using pressurized water. The calibrated DEM simulations satisfactorily fit the experimental results both in terms of $q - \epsilon_z$ curve and of stiffness of granular packing (i.e. E^*_{50}) confirming the effectiveness of this numerical approach.

A secant elastic modulus, instead of a classical initial modulus, is proposed in this work. It seems more meaningful in order to investigate the range of rigidity of medical devices which exploit granular jamming controllable stiffness mechanism. The numerical sensitivity analysis shows that the secant modulus is significantly influenced by the confining pressure (i.e. vacuum pressure ΔP) and secondarily by the contact stiffness between grains (i.e. bulk grain material). The former permits to control the stiffness of the packing up to high strain values ($\epsilon_z \sim 2 \cdot 10^{-2}$), while the latter plays a significant role only for small strains ($\epsilon_z < 5 \cdot 10^{-3}$). However, for practical applications the vacuum pressure still represents the most feasible tuning variable without changing the granular material.

Additional experimental tests, as the bending tests, and other variables, as the particle shape or the particle roughness, should be studied to complete the characterization of granular packing stiffness for a more efficient design of controllable stiffness medical devices.

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