Discrete Element Modeling of Free-standing Wire Reinforced Jammed Granular Columns

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Abstract The use of fiber reinforcement in granular media is known to increase the cohesion and therefore the strength of the material. However, a new approach, based on layer-wise deployment of predetermined patterns of the fiber reinforcement has led self-confining and free-standing jammed structures to become viable. We have developed a model to simulate fiber reinforced granular materials, which takes into account irregular particles and wire elasticity and apply it to study the stability of unconfined jammed granular columns.

1 Introduction

Fiber reinforcement is widely used for different types of applications in various materials, such as reinforced polymer, concrete, and soil. A particularly interesting case is the use of fibers in combination with cohesionless granular materials, since the reinforcement acts as an additional "cohesion" to the material. Typical for reinforced granulates are the randomly distributed fibers inside the soil. Alternatively, the wire can be deployed along a predetermined path, creating strong anisotropies. Recently it was shown [1] that with the latter technique self-containing packings can be constructed allowing for load-bearing granular columns. This approach, named "3D rock printing" opens new opportunities for engineering and architectural applications since the structures behave like a solid and yet they are completely reversible - when the wire is removed the grains crumble into a pile [1, 2].

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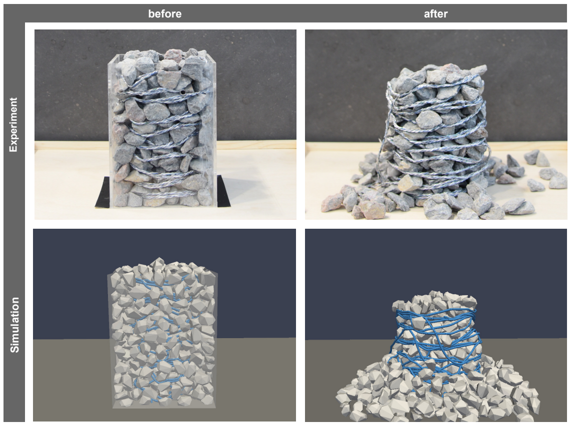
Fig. 1 Free standing fiber reinforced granular columns constructed by first depositing grains and wire inside a rectangular container and then removing the side walls of the container. Experiment (top row) and simulation (bottom row) showing the structure before (left) and after (right) the removal of the confining walls, source [8].



Over the past few decades, reinforced soils have been studied extensively by numerical [4, 3, 5] and experimental [7, 6] means. Several underlying mechanisms are known to be involved: tensioning of segments of wire, blocking between particles, friction induced sticking of wire wrapped around particles, and geometrical interlocking between individual grains. However, the mechanical behavior of such free-standing structures is not fully understood, since the reinforcement in this case does not only enhance the strength and the cohesion, but has also a confining function.

We present here a discrete numerical model for simulating wire reinforced granular materials that captures all the aforementioned mechanisms described in detail in Ref. [8]. We apply it to study the stability of jammed, free standing granular columns under vertical load, see Fig. 1. Our discrete model incorporates two fundamentally different methods and couples them together, which allows us to capture the irregularities in grain shapes, the frictional interactions, and the elasticity of the wire. It should be noted that the proposed method has a very general scope of applicability, ranging from fiber [3] or geogrid [9] reinforced soils to rockfall protection [10] and beyond.

2 Numerical Modeling

In order to capture the effect of geometrical interlocking between the grains, the particles are represented by angular polyhedrons, or to be more precise spheropolyhedrons, which are a Minkowski sum of a polyhedron and a sphere [11]. The spherical dilation is needed to calculate the overlaps between the particles and the wire. Note that this modification does not change the contact calculation between the particles. The interactions between the particles are carried out by means of the Non-Smooth Contact Dynamics (NSCD) method, originally proposed by Moreau [12]. The main scope of applicability of this method is the modeling of dense packings of rigid frictional particles with lasting contacts. The NSCD method is based on the volume exclusion constraint and the Coulomb friction law without regularization. The equations of motion for the particles are integrated with an implicit Newton method. The forces and moments for each contact are resolved by an iterative Gauss-Seidel scheme for each time step, until a global convergence is achieved.

The wire is modeled as a chain of point-like masses connected by tensile spring elements and rotational springs attached to each node, which corresponds to a linear-elastic beam model in the continuum limit. Self-interaction of the wire is realized with the Soft Particle (SP) Discrete Element [13] method introduced by Cundall and Strack [14] with a linear spring-dashpot model. Each wire element has a spherocylinder attached to it in order to carry out the overlap computation [15]. The forces of a contact between two elements are distributed to the four involved nodes with weights inversely proportional to their distance from the closest point of contact. The equations of motion for the translational degrees of freedom of the wire nodes are integrated with an implicit Gear predictor-corrector method of 5-th order. Since the NSCD method is implicit, it is unconditionally stable and therefore the time step can be significantly bigger than the one used for the explicit SP method. Hence, it is reasonable to have two different time steps for the two solvers: Δt^{NSCD} and Δt^{SP}. This leads to a sub-cycling procedure in which the positions of the wire nodes are updated n times for every update of the positions and orientation of the particles, where $n = \Delta t^{NSCD}/\Delta t^{SP}$. After the wire nodes are updated, the contact forces between the wire and the particles is averaged over the n wire time steps and added to the particles.

3 Results and Conclusions

Our simulations show a good qualitative as well as quantitative agreement with the laboratory experiments. For the experiment shown in Fig. 1 we have used railway ballast particles, while the wire is a standard textile string and the walls are made out of acrylic glass. The construction of the samples for both experiment and simulation is equivalent: layers of particles and wire are deposited sequentially inside a rectangular container. After the side walls are removed, the structure loses a part of the initial height, since crucial sections of the wire must be tensioned before it can start acting as a confinement and prevent the column from expanding in the transverse direction. This effect was confirmed by our numerical simulations from the time evolution of the elastic strain energy of the wire after the wall removal.

In order to gain a deeper understanding of the mechanical behavior of fiber reinforced jammed columns a large number of different simulations has been performed in order to investigate the behavior of the columns for a broad range of friction coefficients, wire stiffness, and particle size distributions. We observe from our numerical results that higher particle-wire friction can help to obtain higher columns as well as to increase the tension in the wire. In contrast, particle-particle friction does not influence the height of the columns or the fraction of retained particles inside the column, since the irregularities in the particles account for geometric interlocking between the grains. Nevertheless, higher friction between the particles leads to the reduction of the elastic energy on the wire as the forces are distributed on the particles instead of on the wire. Intuitively, wire stiffness also plays an essential role in the stability of the structures, although the strain energy density has been found to decrease when strain resistance is increased. Furthermore, higher stiffness of the wire leads to a higher retained height of the column. We have shown also that larger variations in the particle sizes can be beneficial for the stability of free-standing wire reinforced granular columns.

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