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Virtual Experiments on Coarse-Grained Soil Using X-Ray CT and Finite Element Analysis

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Abstract : Digital rock physics, an emerging field leveraging advanced imaging and numerical techniques, offers a promising approach to investigating the mechanical properties of granular materials without extensive physical experiments. This study focuses on using X-Ray Computed Tomography (CT) to capture the three-dimensional (3D) structure of coarse-grained soil at the particle level, combined with finite element analysis (FEA) to simulate the soil's behavior under compression. The primary goal is to establish a reliable virtual testing framework that can replicate laboratory results and offer deeper insights into soil mechanics. The methodology involves acquiring high-resolution CT scans of coarse-grained soil samples to visualize internal particle morphology. These CT images undergo processing through noise reduction, thresholding, and watershed segmentation techniques to isolate individual particles, preparing the data for subsequent analysis. A custom Python script is employed to extract particle shapes and conduct a statistical analysis of particle size distribution. The processed particle data then serves as the basis for creating a finite element model comprising approximately 500 particles subjected to one-dimensional compression. The FEA simulations explore the effects of mesh refinement and friction coefficient on stress distribution at grain contacts. A multi-layer meshing strategy is applied, featuring finer meshes at inter-particle contacts to accurately capture mechanical interactions and coarser meshes within particle interiors to optimize computational efficiency. Despite the known challenges in parallelizing FEA to high core counts, this study demonstrates that an appropriate domain-level parallelization strategy can achieve significant scalability, allowing simulations to extend to very high core counts. The results show a strong correlation between the finite element simulations and laboratory compression test data, validating the effectiveness of the virtual experiment approach. Detailed stress distribution patterns reveal that soil compression behavior is significantly influenced by frictional interactions, with frictional sliding, rotation, and rolling at inter-particle contacts being the primary deformation modes under low to intermediate confining pressures. These findings highlight that CT data analysis combined with numerical simulations offers a robust method for approximating soil behavior, potentially reducing the need for physical laboratory experiments.

Keywords : X-Ray computed tomography, finite element analysis, soil compression behavior, particle morphology
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