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Determination of Mechanical Properties of Sand Grains by Nanoindentation

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Abstract Determination of the mechanical properties of individual sand grains by conventional material testing methods at the macroscale is somewhat difficult due to the sizes of the individual sand particles (a few μm to mm). In this paper, we used the nanoindentation technique with a Berkovich tip to measure the Young's modulus, hardness, and fracture toughness. An inverse problem solving approach was adopted to determine the stress-strain relationship of sand at the granular level using the finite element method. A cube-corner indenter tip was used to generate radial cracks, the lengths of which were used to determine the fracture toughness. Scatter in the data was observed, as is common with most brittle materials. In order to consider the overall mechanical behavior of the sand grains, statistical analysis of the mechanical properties data (including the variability in the properties) was conducted using the Weibull distribution function. This data can be used in the mesoscale simulations.

Keywords Sand · Mechanical properties · Nanoindentation · Young's modulus · Hardness · Stress-strain · Fracture toughness · Particulate mechanics

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Introduction

Granular materials, such as sand, are conglomerates of discrete particles held together (but not bonded) with significant void space (35–65%). They are unique in that they behave in some respects similar to the other familiar forms of matter, namely, solids, liquids, and gases and in other respects in a dissimilar form. For example, they pack like solids but flow like liquids. Like liquids, they take the shape of the container but unlike them they can adopt to a variety of shapes when they are free standing. Similarly, like gases, they are made of discrete particles with negligible cohesive forces between them. Like solid, they can support load, but unlike a solid, they hardly support any tensile load. In view of their unique behavior, some consider granular materials as the fifth state of matter, alongside, solids, liquids, gases, and plasma. They cannot strictly be modeled as a continuum, yet it is done by considering the movement of particles in the void space under load, akin to the deformation and flow in solids.

Sand is formed largely by erosion and disintegration of larger rocks into particles by natural forces, such as wind, pressure, water, ice, friction, and heat. Over millions of years, such processes have led to the formation of sand of various grain sizes ranging from a fraction of a micrometer to several millimeters. Investigation of the mechanical behavior of sand from granular (mesoscale) to macro