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Phenomenology of rapid projectile penetration into granular soils

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ABSTRACT

Eighty subscale penetration tests were performed to investigate penetration phenomenology in granular media, with impact velocities in the range of 70–300 m/s. The parameter space consisted of (1) four natural and synthetic granular materials, including Ottawa sand, crushed fused quartz, aragonite, and crushed coral, (2) loose and dense packings, (3) dry and wet targets, and (4) four different projectiles, including spheres and long rods with conical, hemispherical and blunt nose shapes. Two techniques were employed to obtain penetration time histories, including photonic Doppler velocimetry for high velocity impact tests, and high speed imaging for low velocity impact tests. Penetration time histories were differentiated to obtain velocity and acceleration time histories. Analysis of the time histories revealed that the role of nose shape, packing density, and saturation is material dependent. Silica sands and calcareous sands showed contrasting behavior across the parameter space considered. These observations point to the significance of particle crushing in rapid penetration into granular media.

1. Introduction

There has been a recent surge of interest in penetration of granular materials. Impact and penetration into granular media is important for many engineering applications, including subsurface investigations, planetary impact, and offshore foundations and anchors, among others [12]. Many aspects of penetration mechanics have been addressed in recent literature. A general picture is emerging in which there appears to be several distinct regimes in the global records of penetration into granular media. These regimes appear with different fidelity in different materials, and they appear to depend on the penetration velocity. The existence of different penetration regimes may point to changes in energy transfer mechanisms at different stages of penetration. This paper is an effort to further investigate these regimes.

The study of rapid penetration into granular media is closely related to their high strain rate response [13]. Thus, study of penetration effects provides both qualitative and quantitative insights into the mechanical properties of granular materials at high stresses and high strain rates. For example, it has been shown that during penetration of an intruder in granular media, networks of stressed particles known as force chains transfer the intruder load to the target media at particle contacts (*e.g.*, [8]). As the magnitude of load carried by the particles increases, displacement of particles results in buckling of these force chains. Load is therefore redistributed along other force chains as new contacts form. Formation and buckling of force chains appears dependent on the penetration velocity due to the time scale associated with these phenomena. Investigating these hypotheses requires observations of penetration dynamics across a wide range of penetration velocities.

In this paper, results of experiments performed with projectiles penetrating various granular media are reported. Two methods were employed to measure time history of projectile penetration; *photonic Doppler velocimetry* (PDV) for spherical projectiles impacting at 300 m/s and *high-speed imaging* (HSI) for rod projectiles penetrating at 50–100 m/s. Three natural sands and one synthetic material were tested, and the penetration histories were recorded. In the following sections, first, the experimental setups used to obtain penetration time histories in various materials and using different projectiles are briefly described. Next, observations of penetration dynamics along with general patterns observed from the tests in various materials are reported. Finally, the observed response is related to the phenomenology of rapid penetration into granular media.

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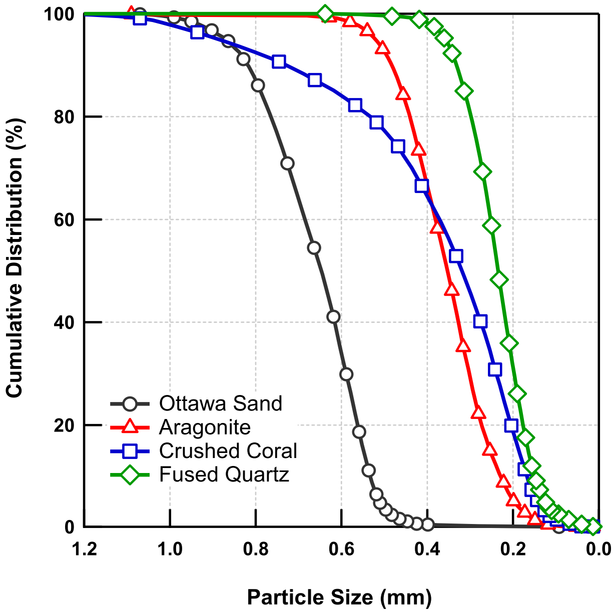

Fig. 1. Particle size distribution of four granular media tested.

2. Experiments

2.1. Granular media

Four different granular media were tested in this study (Fig. 1). The materials were selected to cover a range of parameters representative of natural and synthetic granular media, including specific gravity, packing density, particle shape, mineralogy, and internal flaws. Several standard characterization tests were performed on the tested media, including minimum and maximum density measurements according to ASTM D4254 [3] and ASTM D4253 [2]; specific gravity according to ASTM 854 [4]; and particle size distribution according to ASTM 6913. In addition to the aforementioned characterization, typical particle shapes were also characterized using a dynamic imaging particle size analyzer (Sympatec QicPic). Typical 2D projections of particle shapes corresponding to the median diameter, by weight, known as d_{50} were obtained (Fig. 2). Particles were characterized using sphericity, ψ, and aspect ratio, A_R. Sphericity is defined as the ratio of the surface area of a sphere with the same volume as the given particle to the surface area of the particle, and aspect ratio is defined as the ratio of the largest diameter to the smallest diameter orthogonal to it. Distribution of sphericity with particle size is shown in Fig. 2 for the four tested materials, which are as follows:

- ***Ottawa sand***, which is a siliceous sand with a particle specific gravity of 2.65. The size distribution of the particles is shown in Fig. 1. Ottawa sand has a narrow size distribution, classified as poorly graded sand (SP) in the *Unified Soil Classification System* (USCS) (ASTM D2487 [1]). Ottawa sand is comprised mainly of round particles (Fig. 2), having a d_{50} of 0.65 mm, median sphericity of 0.90. Minimum and maximum densities of the Ottawa sand were 1.56 g/cm^3 and 1.83 g/cm^3, respectively.
- ***Crushed fused quartz,*** a product of grinding fused silica glass, is also classified as SP according to USCS. Crushed fused quartz consists of 99% SiO_2, and has a specific gravity of 2.20 [20]. Unlike Ottawa sand, it is amorphous; presumably the grains are much stronger, since there are no sub-grains that can break apart. The material is comprised of angular particles, having d_{50} of 0.21 mm, with a median sphericity of 0.83, but with a broad distribution of particles with smaller sphericity down to approximately 0.45. Minimum and maximum densities of the tested crushed fused quartz were 0.99 g/cm^3 and 1.31 g/cm^3, respectively.
- ***Aragonite sand*** is an oolitic calcium carbonate based granular material with round particle shapes, as shown in Fig. 2. Aragonite results from precipitation of calcite; the particles have a specific gravity of 2.74, which is higher than the other materials tested. Aragonite was chosen because it resembles the sphericity of Ottawa sand, but is more susceptible to crushing. The tested Argonite has a d_{50} of 0.38, with an average sphericity of

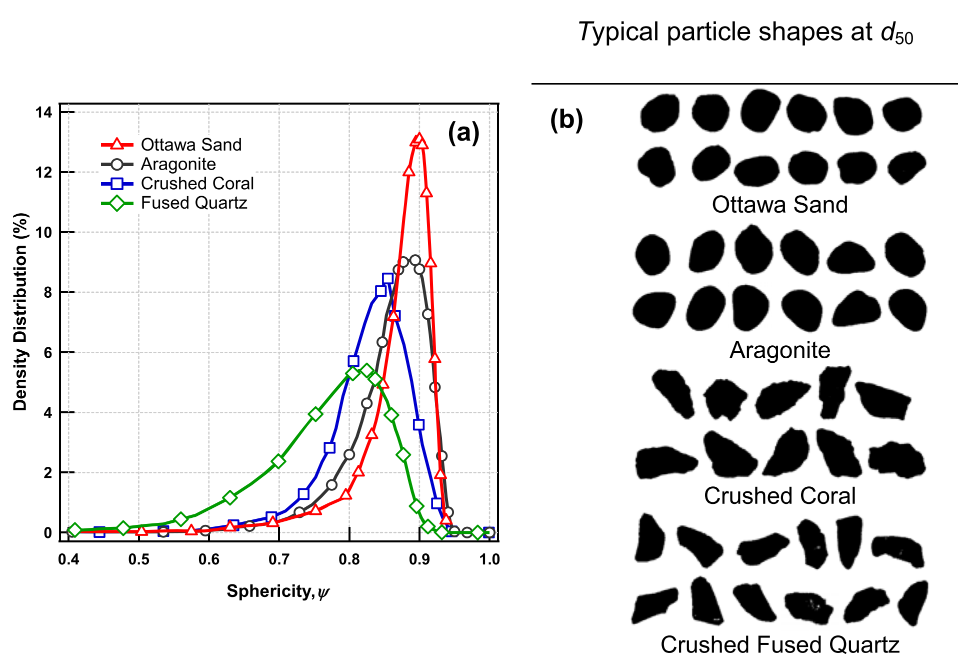

Fig. 2. (a) Density distribution of particle sphericity, and (b) Typical two dimensional projections of particle shapes for granular media tested.