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# Observations of projectile penetration into a transparent soil

Ivan L. Guzman[a], Magued Iskander[b,*], Stephan Bless[c]

[a] Civil and Environmental Engineering Department, New Jersey Institute of Technology, Newark, NJ 07102, United States
[b] Civil and Urban Engineering Department, NYU Polytechnic School of Engineering, Six Metrotech Center Brooklyn, NY 11201, United States
[c] NYU Polytechnic School of Engineering, United States

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ABSTRACT

In this study, a transparent sand surrogate was employed along with high-speed imagery to un-intrusively visualize the penetration of a spherical projectile into the center of a saturated granular target, representing angular sand, at speeds ranging between 60 and 150 m/s. The transparent sand was made by saturating an angular granular fused quartz waste product with a matched refractive index pore fluid made of sucrose. A distinct zone of opacity was observed traveling ahead of the projectile. The opacity zone appears circular during initial penetration and transitions into the shape of an elongated cone in shots with higher initial velocities. Some healing was also observed with time and some increase in transparency was observed. Some of the opacity is attributed to dilatancy of the granular fused quartz during penetration, and healing is attributed to flow of pore fluid into the dilated zone.

## 1. Introduction

Phenomenology associated with impact cratering onto granular and solid materials has been a topic of much interest in recent years [33,44] and the field has also been covered in two recent review articles [36,37]. Impact cratering has been studied both by creating numerical models to understand the penetration phenomena and experimentally. Numerical models have been used to model penetration into oblique targets [10] where the angle of impact, a more common event in nature, is different from vertical impact which is more commonly studied. Others have used existing shock physics codes to understand how the target properties affect cratering [40,41]. Glass sphere targets in combination with gas guns and occasionally laser sheets have been also used to study crater growth during penetration into granular materials [4,45,46]. Experimental techniques have also been introduced to study hypervelocity impacts into solid materials such as porous sandstone and basalt/pyrex specimens [7,20,28]. The penetration process through opaque materials has also been visualized by the use of a transparent observation window adjacent to the projectile trajectory, a technique commonly known as quarter space. Evolution of explosive craters in sand was extensively studied with this technique by Piekutowski [38]. The technique has also been applied to penetration into granular materials [5,6,42]. However, the quarter-space technique can lead to wave reflections at the window which possibly influences the crater formation process. Although there is much data concerning penetration depth as a function of impact velocity, there are very few observations of transient craters and cavities caused by penetrating projectiles. Technically speaking a crater is a cavity that opens to the surface.

The study of penetration events into granular media is of special interest to many engineering problems such as explosions and air blasts, earthquakes, mine blasts, vehicle and aircraft wheel loading, dynamic compaction, pile driving and rapid load testing of piles and projectile penetration. This study presents an experimental technique to non-intrusively observe the formation and development of impact cratering at all stages of penetration with the use of a transparent soil surrogate. It is important to note that impact processes in the hypervelocity regime, as those associated with cratering from a planetary perspective, require significantly higher impact velocities than the ones used in this study. However, the experimental techniques introduced herein can be modified in future studies for observation of hypervelocity impacts and the study of shock-wave induced crater formation.

Observation of crater dynamics is made possible by use of a transparent soil. Transparent soils are surrogates of natural soils that are made by matching the refractive index (RI) of particles and a saturating pore fluid to minimize refraction of light. Transparent soil surrogates have been used in model tests to study flow or deformations, and to study quasi-static penetration into sand and clay [1,2,11,13,14,19,21–26,29–32,34,39,43]. Recently, transparent soil surrogates have also been used to assess and study depth of penetration of spherical projectiles into transparent sand [18]. In the

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[*] Corresponding author. Tel.: +1 646 997 3016; fax: +1 646 997 3136.
*E-mail addresses:* iguzman@njit.edu (I.L. Guzman), Iskander@NYU.edu (M. Iskander), sb4326@nyu.edu (S. Bless).

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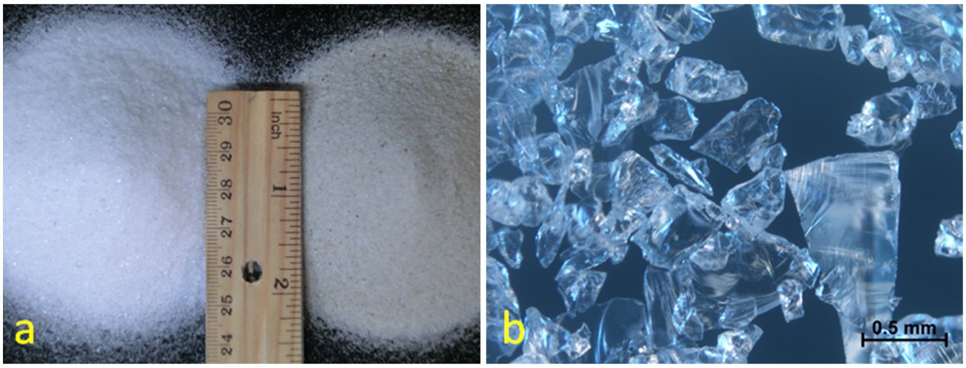

**Fig. 1.** Photograph of granular fused quartz (a) comparison of granular fused quartz (left) and Ottawa sand (right) (b) magnified image of granular fused quartz.

present study, the same material was employed to visualize not only the terminal depth of penetration, but also observe the effect of the penetration on the penetrated medium. Depth of penetration, in this study, refers to penetrative low-velocity impacts such as those from meteoric impacts after velocity reduction due to the atmosphere.

In general, the term "soil" refers to natural granular earthen materials that result from the weathering of natural rock. In lieu of available natural transparent soils, this study uses a previously introduced synthetic transparent soil surrogate. The transparent soils used in this work were comprised of granular fused quartz glass, Fig. 1, combined with a refractive index-matching liquid made of sucrose [15,16]. Granular fused quartz glass used herein is from the same manufacturer and have similar gradations to fused quartz used in those studies. These studies and others [12] have shown that the quasi-static rheological and geotechnical properties such as shear strength, compressibility, particle breakage and grain size distribution of these mixtures, closely resemble those of natural sands.

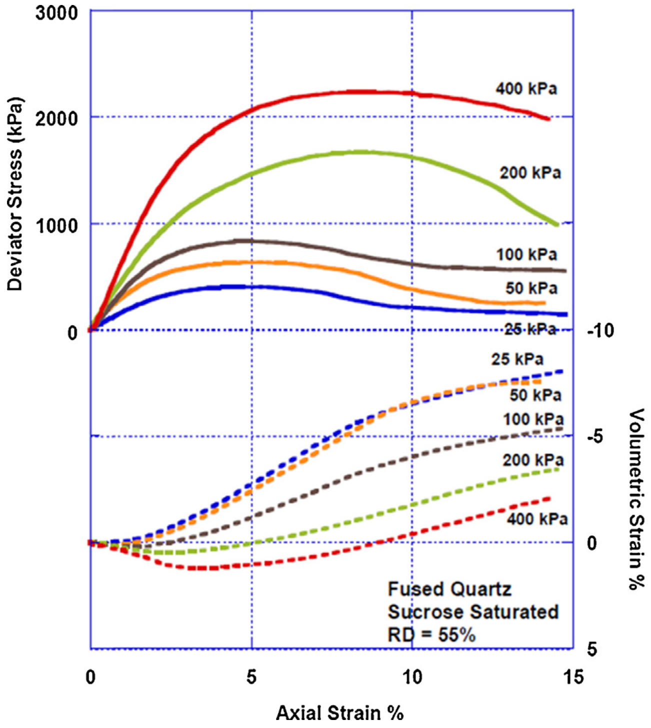

**Fig. 2.** (Left) Stress versus axial strain, and volumetric strain versus axial strain curves of sucrose saturated granular fused quartz under triaxial compression, contractive volume change is positive, dilative is negative.

## 2. Experimental setup

### 2.1. Materials

Granular fused quartz used in this study had a gradation of particles that passed the #20 sieve and were retained on the #60 sieve [3] and is thus designated as FQ(−20 + 60), or simply FQ. The maximum and minimum dry densities of FQ were determined to be 1.30 and 1.00 g/cm$^3$, respectively. The axial stress versus axial strain, and axial stress versus volumetric strain of granular fused quartz under triaxial compression is shown in Fig. 2. It can be seen that sucrose-saturated granular fused quartz under low confining pressure exhibits a highly dilative response during axial compression. Dilatancy in this study refers to an increase in total volume due to a change in shape. The particle size distribution for FQ and other natural soils is presented in Fig. 3.

The state of compaction of granular materials is commonly characterized by using the relative density scale. This refers to the relative compaction of a granular material at the time of testing in relation to its maximum and minimum compaction achievable with standardized laboratory procedures. Relative density has a scale of 100 (most compact) to 0% (most loose), with generally agreed subdivisions of 100–80% (very dense), 80–60% (dense), 60–40% (medium dense), 40–20% (loose), and 20–0% (very loose).

Transparent targets were prepared by pluviating (raining) FQ into a container half full with the saturating fluid. The technique of pluviating through several inches of saturating fluid serves two purposes; first, it creates a soil structure that mimics natural sedimentation at a controlled relative density; and second, the presence of a standing layer of liquid "filters" the air bubbles, a major source of transparency degradation, which improves the transparency of the specimens. Pluviation through the pore fluid produced very loose specimens with a relative density on the order of 10–15%. Dense specimens were prepared by using an electro-mechanical vibrator (Fritsch model Analysette 3 Pro), operated at an amplitude of 0.1–0.4 mm until the desired relative density was achieved. To ensure correct densities, vibration was conducted until a known quantity of soil occupied a predetermined volume previously marked on the transparent containers. Weight measurements of the container plus saturating fluid were recorded prior to and after pluviation to determine the volume fraction of solids deposited and thus the dry density, and relative density of the model soil. The total (bulk) density was then calculated by assuming 100% saturation. Dry density is defined as the weight of the solid portion of the soil structure (granular particles) divided by the total volume of the soil structure, which is constant regardless of saturation conditions (dry or wet).