International Journal of Impact Engineering 89 (2016) 72–82

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

High-resolution X-ray and neutron computed tomography of partially saturated granular materials subjected to projectile penetration

Felix Hoyean Kim [a], Dayakar Penumadu [a,*], Nikolay Kardjilov [b], Ingo Manke [b]

[a] Department of Civil and Environmental Engineering, The University of Tennessee Knoxville, 851 Neyland Drive, 325 John D. Tickle Building, Knoxville, TN, 37996-2313 USA
[b] Helmholtz Center Berlin for Materials and Energy, Hahn-Meitner-Platz 1, 14109 Berlin, Germany

ARTICLE INFO

Article history:
Received 23 January 2015
Received in revised form 3 November 2015
Accepted 5 November 2015
Available online 12 November 2015

Keywords:
Partially saturated sand
Projectile penetration
Neutron
X-ray
Computed tomography

ABSTRACT

To improve fundamental understandings of projectile penetration through partially saturated sand at a meso-scale and provide controlled experimental data to validate future numerical simulations, high-resolution computed tomography of granular materials after projectile penetration using two different imaging modalities (X-rays and neutrons) was implemented. This paper presents the novel imaging techniques and results of studying the variation of geometric structure (arrangement of solids, voids, liquid films) at a meso-scale after the penetration of projectiles (ex-situ) under controlled conditions. Attenuation contrast obtained from X-rays and neutrons provided complementary information that would not have been possible to obtain by using X-rays only. X-rays identified silica particles and their boundaries at 14.8 μm/pixel resolution, while neutrons spatially resolved small amounts of moisture at 15.6 μm/pixel resolution due to a large neutron cross-section of hydrogen. Lead (Pb) contained in most projectile tips is opaque to X-rays but transparent to neutrons at the energy range generally used for imaging. Indeed, the need for using multi-modal imaging is further emphasized for non-invasive damage diagnostics. Partially saturated crystalline sand specimens with bulk gravimetric water contents of 5~6% were studied at two different initial packing states (dense and loose) using two different types of commercially available projectiles. A novel image registration technique combined 3-D attenuation data obtained at different spatial resolution with two imaging modalities (X-ray and neutron). The role of moisture in sand on penetration resistance and related effects on the meso-structure has not been studied in detail in the past, and the results from the current study show important preliminary insights on this topic. The effects of projectile impact and penetration on particle rearrangements, fractures, and water re-distributions are summarized as a function of the initial specimen state of compaction and projectile parameters (mass, impact velocity, twist during penetration, and with use of full metal jacket ammunition). Observations of damage patterns including penetration depth and cavity formation are summarized in this paper, and the findings form an important basis for an improved understanding of penetration mechanics in porous materials and related multiscale modeling framework.

1. Introduction

Penetration mechanics of granular or particulate materials are complex due to the discrete nature of the materials, and the problem involves the complex effects of varying strain rate, temperature, and particle fracture. When partially saturated, the interactions between solid, liquid, and gas phases make the material even more complicated, especially for penetration of projectiles due to the coupled effects of multi-phase mechanics and fluid hydraulic/transport behavior. Due to the discrete nature of granular materials, different initial microstructures with widely varying pore size distributions possibly can occur, depending on the past loading history and compaction process. The amount and distribution patterns of liquid films and/or bridges also have considerable effects on the deformation behavior of an assemblage of frictional particulates.

Events with high-strain rates resulting from a projectile penetration [1] or explosions/blast loading [2] are difficult to evaluate in isolation since the non-linear stress-strain behavior of granular materials (such as sand) are dependent on various factors. These factors include the initial state of assembly, past stress history, effective, hydrostatic and deviatoric stresses (effective stress represents the difference of total stress and pore water pressure), inherent and stress induced anisotropy, partial saturation state, and tendency for the occurrence of strain localizations.

Strain rate affects the response of soil tremendously [3]. A stress–strain curve at an intermediate strain rate can be obtained from a

* Corresponding author. Department of Civil and Environmental Engineering, The University of Tennessee Knoxville, 851 Neyland Drive, 325 John D. Tickle Building, Knoxville, TN, 37996-2313 USA. Tel.: +1 865 974 7708; fax: +1 865 974 2669.
E-mail address: dpenumad@utk.edu (D. Penumadu).

http://dx.doi.org/10.1016/j.ijimpeng.2015.11.008
0734-743X/

split Hopkinson pressure bar test, and such properties were measured for both dry and partially saturated sand recently [4–7]. Challenges to correctly measure rate-dependent behaviors of granular materials largely exist due to difficulty in achieving a dynamic stress equilibrium in a split Hopkinson pressure bar setup as well as meeting the requirements of a cleverly designed pulse shape and a long transmission bar made of a lower impedance material (such as polymer) to transfer stress effectively. Various parameters including initial void ratio and degree of saturation affect projectile penetration through sand. Void ratio and degree of saturation are global parameters evaluated for a deforming specimen based on gravimetric data and specific gravity of solid particles. The fabric (geometric arrangement of particles) and force chain structure also have an important influence on load transfer mechanisms in granular materials using analogous photo-elastic discs [8].

Sand has often been used for ballistic protections against explosive materials that actuate munitions [9]. There has been a high interest in understanding its response to impact type of loading and subsequent penetrations of projectiles. The penetration mechanics of projectiles through concrete are governed by the factors similar to those of projectile penetration through granular materials such as sand.

Allen et al. [10] reported results from early experiments involving a non-rotating, conical-nosed projectile on randomly-packed sand at an impact velocity of 700 m/s. The projectile was approximately 130 mm long and 13 mm in diameter having a mass of 80 g with a hollow region at its tail. The angular quartz sand had an average diameter of about 1 mm which was placed in a steel chamber with 0.3 m × 0.3 m in cross section and 1.8 m long. The main focus of their experiments was to determine penetration depths of projectiles with different cone angles. Based on the results, a simple theory of projectile penetration was proposed.

Cooper and Breaux [9] performed projectile penetration tests with two different speeds (600 m/s and 1200 m/s) of projectile for two different initial densities (1.55 g/cm^3 and 1.73 g/cm^3) of sand. The projectiles had hemispherical nose shapes. Sand was placed in a relatively large steel box (60 cm × 60 cm × 240 cm). Mesh screens were used in the compacted sand assembly at a suitable spacing to estimate the time and path of projectile during the penetration process. They also studied fractured sand particles with light scattering and scanning electron microscopy (SEM) techniques. They additionally discussed the effect of different length scales (micro, meso and macro scales). For example, meso-scale is defined as the representative volume element (RVE) scale where individual grains can be recognized and counted.

Watanabe et al. [11] performed penetration tests while acquiring high-speed optical images of the initial impact at the surface and subsequent penetration through sand to determine velocity and penetration depth. Samples were prepared at bulk densities of 1.49~1.56 g/cm^3. The arrival time and trajectory of projectile through sand were detected by using optical glass fibers embedded in the sand samples. They discussed the effect of the sample container on penetration depth for different impact velocities.

Borg et al. [12] used a particle image velocimetry (PIV) setup to monitor a projectile penetration test. A polycarbonate tank (35 cm × 25 cm × 18 cm) was built and filled with Ottawa sand at bulk density of 1.56 g/cm^3. Images were recorded during the projectile penetration, and they were correlated to stress profiles over time. Velocity vectors were obtained based on the analysis of PIV images.

A majority of the experimental works performed to date has been carried out at a relatively large macro-scale. A recent research work indicates the importance of looking at multiscale (macro, meso and micro) to fully understand the failure phenomena associated with the penetration of a rigid projectile and correctly model the physics of the problem [13]. In order to capture the effect of the discrete and particulate nature of sand and improve understanding at different length scales, more experiments need to be performed at meso-scale. Most of the relevant past experiments were performed using dry sand, and the effect of pore fluid has not been considered. Water is inevitably present in a sand assemblage in nature, and it is important to give further attention to the effect of pore fluid on projectile penetration.

While dynamic responses of sand during and after projectile penetration can be monitored using high-speed optical microscopy, the response in the microstructure is not possible to obtain. Granular materials can also be easily disturbed during the extraction or slicing process for interior visualization (i.e. when using electron microscopy of resin impregnated samples). Non-destructive techniques to visualize the microstructure of sand after projectile penetration are needed.

Radiation based imaging is a powerful tool to investigate the internal structure and defects of materials non-destructively in three dimensions (3D). For an imaging experiment to be successful, parameters such as time scale of the event, spatial resolution needed, and contrast of the materials of interest need to be considered. Radiography and computed tomography (CT) are the two general modes of imaging. Radiography obtains a two dimensional (2D) image through the thickness of a sample, and CT combines multiple 2D radiographs at different angular orientation of the sample to obtain 3D information. Many dynamic events occur extremely fast in time scale (μs~ms), and a dynamic radiography mode is often employed in order to investigate dynamic phenomena in-situ. A few recent research works used X-ray radiography to study projectile penetration through sand or other granular materials [14,15]. While valuable information on the dynamic process of projectile penetration can be obtained from radiographs, the information is still limited to 2D. Three-dimensional failure and damage processes are often difficult to interpret from a radiograph only, and the projectile penetration path in 3D is also unknown. Recent developments of high-speed flash X-ray CT technique provide an in-situ CT of a dynamic process at a single point in time [16]. However, the spatial resolution is limited to about 1 mm at the current configuration which is too coarse to investigate the original and crushed sand particles (<500 μm). Recent advances in X-ray imaging technique can readily provide image resolution at a micron scale by using laboratory microfocus X-ray systems and at a sub-micron scale at Synchrotron imaging facilities. Such high-resolution CT scans provide information at meso to micro scales well-suited for the evaluation of damage resulting from a projectile penetration through porous media and related multiscale phenomena. X-ray CT techniques were used to investigate projectile penetration mechanics through various materials recently (e.g. references 17–19). While the X-ray CT technique has also been used to study quasi-static failure of sand or soil specimens (e.g. references 20,21), the technique has not been used to study soil specimens after projectile penetrations prior to the current study.

Some materials are either too transparent or opaque to X-rays to diagnose through the use of images. In such cases, a different imaging modality such as neutrons can be considered to improve contrast of the material. For example, water has low contrast in an X-ray image, especially at a high energy range (> 100 keV), but it shows high contrast in a neutron image. Neutron imaging is a relatively newer technique compared to X-ray imaging. A state-of-the-art neutron imaging facility currently provides image resolution on the order of ten microns, comparable to that of a microfocus X-ray system. A different imaging modality often provides better contrast on target features of granular materials and a buried projectile. Recently, the authors quantitatively evaluated three phases (sand, air and water) of partially saturated sand specimens by using both neutron and X-ray imaging at high resolution [22], and also developed a novel methodology to combine the dual-modal (X-ray and