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Uniaxial compressive behavior of partially saturated granular media under high strain rates

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ABSTRACT

This paper targets gaps in current literature pertaining to the influence of strain rate and particle shape on the dynamic compressive response of partially saturated porous media as a function of saturation. The extent of particle breakage in response to variations in saturation is also explored. Two materials consisting of Stockton Beach sand and glass beads with saturations ranging from 0% to above 90% under strain rates between 800 s^{-1} and 2100 s^{-1} were investigated via the split Hopkinson pressure bar. All specimens exhibited an initial void ratio of 0.68 (porosity of 0.40) and were confined within a hardened steel tube effectively inhibiting lateral expansion. The stress–strain of dry specimens was found to be invariant with respect to loading rate, but experimental results for samples with saturations between 25% and 75% prior to water lock-up suggest an increase in overall compressibility under higher strain rates. The shape and mechanical properties of individual grains was also shown to influence the sample response. With the addition of water, the compressibility of glass beads relative to the dry response was demonstrated to be much higher than that of the beach sand. The extent of grain crushing witnessed for Stockton Beach sand as quantified via Hardin's relative breakage potential was also characterized for specimens retrieved post-impact. It was found that crushing decreased linearly with increasing saturation under a given rate of strain.

1. Introduction

Granular materials in the context of soil mechanics encompass a wide variety of soil types incorporating pore fluids at any saturation from dry to complete saturation. Traditionally, the mechanical characterization of materials such as sand for geotechnical purposes has primarily focused on either dry or fully saturated conditions [1–6]. Extending this understanding into the dynamic regime under partially saturated conditions is paramount for a range of engineering applications. By characterizing and predicting the response of partially saturated sand at high rates of strain, solutions can be proposed to challenges such as calculating the impact of landmines [7], investigating damage to underground structures from explosions [8], determining stress wave propagation in soils under blast loading [9] and dynamic compaction [10], estimating the depth of projectile penetration in soils [11], supplying vibrational isolation and shock absorption for engineering systems [12], and understanding earthquake induced loads on structures [13].

However, the high strain rate behavior of geological materials is significantly less understood when compared to metallic substances [14]. Experimental characterization of porous geological materials under high strain rates present numerous difficulties due to low wave speed, high acoustic energy attenuation, and lack of structural strength [15]. This has contributed to an absence of standardization in test procedures and regimes, resulting in a lack of experimental data pertinent to the dynamic response of granular materials [16].

Despite such difficulties, researchers have attempted to investigate the response of both dry and partially saturated sand under high strain rate conditions via the split Hopkinson pressure bar (SHPB). Song et al. [17] performed compressive SHPB tests with pulse shaping on a fine grained silica sand with most particle sizes falling between 150 and 450 μm at strain rates up to 1450 s^{-1}. The material was confined using tubes manufactured from 4340 steel, polycarbonate, and polyolefin in decreasing order of stiffness. The objective was to quantify the dry dynamic compressive stress–strain response in terms of strain rate, initial dry density, and confinement pressure. Bragov et al. [18] extended the high strain rate testing of dry quartz sand confined in a rigid steel jacket beyond the SHPB via the inclusion of plate impact experiments. This allowed for applied pressures to exceed 3 GPa with specimens experiencing strains of more than 45% and strain rates up to 10^6 s^{-1}. The inclusion of a strain gauge on the outer wall of the confining cylinder also enabled the quantification of radial strains. It was thus identified that while increasing the initial density and confinement pressure of dry sand facilitates an increase in the confined modulus, the stress–strain

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response of such materials are invariant with respect to strain rate. In terms of dynamic testing on partially saturated porous media, Veyera [19] implemented standard SHPB experiments on compacted Eglin, Tyndall, and Ottawa 20–30 sands exhibiting water saturations ranging from 0% to 100% at strain rates of 1000 s^{-1} and 2000 s^{-1}. It was observed that increasing the moisture content resulted in the initiation of water lock-up phenomena (defined as the state at which the sample stress–strain behavior approaches that of pure water under dynamic compression) at lower strains. Unfortunately, the influence of strain rate on the stress–strain response could not be identified within that study due to high degrees of uncertainty within the experimental results. Additional work to investigate the high strain rate behavior of partially saturated sand was performed by Felice et al. [20]. Standard SHPB tests were conducted on compacted clayey sand specimens at the optimum moisture content of 13.3% and dry density of 1.87 g/cm^3. Under strain rates between 1000 s^{-1} and 4000 s^{-1}, it was suggested that the dynamic stress–strain response may be influenced by the rate of applied strain for partially saturated specimens. However, the authors of that study cautions against drawing any definitive conclusions regarding strain rate dependency, addressing that additional experiments are required to confirm such behavior. More recently, Martin et al. [14] conducted uniaxial compressive SHPB experiments with pulse shaping on a fine grained silica sand with an initial dry density of 1.50 g/cm^3 at a constant strain rate of 400 s^{-1}. The objective was to investigate the effect of saturation as it is varied from 11% to 70% on the overall stress–strain behavior. It was concluded that partially saturated samples are more compliant than its dry counterpart with the softest response occurring at 25% saturation. The authors of that study attributed the greater compliance of sands at low saturation to the lubricating effect of pore water. It was proposed that low saturation reduces inter-particle friction, thus decreasing localized shear stresses while facilitating smoother particle rearrangement [14].

In addition to stress–strain response, particle breakage is also critical to understanding the mechanisms governing the mechanical response of granular material. Grain crushing under dynamic loading pertains not only to civil engineering applications [21] but is also of interest within fields of food processing and pharmacology [22]. Crushing relates to the fracturing of individual particles as the stresses imposed on the grains exceed their strength [23]. In dry conditions, numerous properties and parameters have been found to influence the extent of particle breakage including initial void ratio, particle size, particle gradation, particle angularity, confinement environment, and material composition [24–26]. However, the influence of moisture in governing crushing behavior under dynamic conditions has received limited attention throughout the literature. Accurately quantifying the extent of particle breakage for granular materials as a function of saturation must therefore be implemented. This can be achieved via Hardin's relative breakage potential index [27] which considers the crushing of all particle sizes above 0.074 mm via integration of the complete post-test grading curve. Hence, Hardin's method is commonly adopted in the evaluation of grain crushing for granular materials under quasi-static and dynamic loading conditions [23,25,28].

Earlier research has been paramount in achieving a fundamental insight into the mechanical behavior of granular media under dynamic conditions. In particular, many past studies examining the response of dry sand under rates of strain from quasi-static up to 10^6 s^{-1} concluded that varying the strain rate produced a negligible effect on the overall stress–strain response [17,18,29–31]. The introduction of moisture into specimens as performed by Martin et al. [14] and Veyera [19] respectively allowed for the observation of partially saturated behavior both before and after the initiation of water lock-up phenomena as a function of the saturation. An accurate description of post-impact grain crushing can also be achieved via Hardin's relative breakage potential index. Despite such efforts it is evident that more work is required to better understand the high strain rate behavior of partially saturated granular materials. Thus far, the effect of strain rate on partially saturated sand is still unclear. Experimental data in the literature usually fails to produce definitive conclusions regarding the strain rate dependency of partially saturated granular media [31]. In addition, the impact of particle shape on the dynamic response has received scant attention. It is understood that irregularly shaped grains are more prone to breakage than that of well-rounded particles due to the presence of asperities susceptible to local stress concentrations [31,32]. While a more compliant response under compression is expected for grains exhibiting greater angularity, it remains unclear what effect the introduction of water would have on specimens of differing grain geometries. Thus, further research is required to systematically explore the influence of strain rate and particle shape as a function of saturation on the dynamic behavior of unsaturated granular materials.

This paper characterizes the uniaxial compressive dynamic stress–strain response of two types of fine grained granular media tested via the SHPB under different rates of strain and saturations. Samples consist of Stockton Beach sand and glass beads, which enables insight into the high strain rate behavior of grains with different geometries and mechanical properties. Both materials exhibit similar particle size distributions and are maintained at a constant initial void ratio confined within a steel tube. The implementation of pulse shaping enabled the facilitation of dynamic stress equilibrium and constant rate deformations to satisfy the requirements for the valid extraction of SHPB results. The primary objective is to determine the influence of strain rate and saturation on stress–strain behavior while quantifying any differences observed between the two materials considered. Hardin's relative breakage potential was also applied to evaluate the extent of grain crushing on sand specimens retrieved post-impact. Experimental observations will therefore enable a systematic overview of the factors affecting the high strain rate response of partially saturated granular media. This acts to ultimately aid the development and validation of constitutive models applicable to the dynamic characterization of such materials.

2. Experimental configuration

2.1. SHPB setup

The split Hopkinson pressure bar is commonly used for characterizing the high strain rate response of engineering materials [33]. Originally developed for the testing of metallic specimens, the SHPB has been increasingly employed for exploring the high strain rate responses of soft porous materials such as sand and clay [31,34]. Conceptualized by Hopkinson [35] and refined by Kolsky [36], the device enables an indirect measurement of the dynamic strain–stress response of a specimen sandwiched between two rods (known as the incident and transmitted bars). A third rod (the striker bar) is launched at speed into the incident bar which results in the propagation of a compressive stress wave through the pressure bars and specimen. Due to the impedance mismatch between the sample and pressure bar, a portion of this pulse is reflected at the specimen/incident bar interface as a tensile wave bouncing back towards the impact end of the input bar, while the remaining pulse is transmitted into the specimen and then the transmitted bar. The incident and reflected strain histories are typically recorded via a strain gauge attached on the incident bar while the transmitted strain is collected by a gauge on the transmitted bar. Provided that the pressure bars remain linear elastic throughout the test and that dynamic stress equilibrium is achieved, the stress history of the specimen may be