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Influence of dry density and confinement environment on the high strain rate response of partially saturated sand

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ABSTRACT

The high strain rate compressive response of partially saturated Stockton Beach sand is investigated using the modified split Hopkinson pressure bar. The objective is to determine the influence of initial dry density and confinement environment on the stress–strain response, energy absorption, and grain crushing of Stockton Beach sand at average strain rates between 1000 and 1300 s^{-1} as a function of saturation. Specimens are confined within a hardened steel tube, and exhibit dry densities of 1.46 g/cm^3, 1.57 g/cm^3, and 1.69 g/cm^3 with saturation ranging from 0% to above 90%. Samples with 1.57 g/cm^3 density are also confined via polycarbonate chambers with two different wall thicknesses. It can be observed that the stress–strain response of partially saturated sand generally stiffens with increasing initial dry density prior to water lock-up, while stiffening decreases with increasing saturation. An increase in confinement rigidity causes a rise in stiffness with lock-up occurring only in specimens confined in steel chambers. Energy absorption at a given stress level generally increases with decreasing initial dry density and softer confinement. Grain crushing witnessed for partially saturated sand, quantified by Hardin's relative breakage potential, is retrieved for post-impact inspection. Crushing is found to increase with both initial dry density and confinement rigidity, and decrease linearly with saturation. Experimental results derived from this study will aid in the calibration and validation of multi-phase constitutive models for predicting the dynamic response of partially saturated porous media.

1. Introduction

The ubiquity of sand as a construction and mining material accentuates the importance of accurately capturing its dynamic response for applications across industrial sectors ranging from civil and mining to defense. However, the behavior of sand under high strain rate loading is infrequently characterized and poorly understood. The incorporation of water giving rise to a partially saturated state further exacerbates the challenges in evaluating the overall response of sand under impact. In addition, the advent of numerical simulations via constitutive models for engineering assessment and design necessitates the extraction of reliable material data for calibration purposes [1]. Experimental characterization of the dynamic behavior of granular materials is therefore essential for applications in mining, blast, and earthquake engineering [2–6].

Physical tests on sand under high strain rates present numerous difficulties due to low wave speeds, high acoustic energy attenuation, and low material strength [7]. This results in the absence of standardized test procedures and regimes, and the consequent limited availability of reliable experimental data [8]. Nevertheless, the split Hopkinson pressure bar (SHPB) remains a popular tool in evaluating the compressive high strain rate response of granular media in general, including sand, under various high strain rates, densities, and confinement conditions. SHPB tests were performed by Song et al. [9] and Kabir et al. [10] on dry samples of a fine-grained sand with densities of 1.50 g/cm^3 and 1.62 g/cm^3 at strain rates up to 1450 s^{-1}. Specimens were contained within cylinders made of steel, polycarbonate (PC), and polyolefin to simulate different levels of confinement. In those instances, it was demonstrated that the uniaxial stress–strain response of dry sand is insensitive to strain rate but highly influenced by initial dry density and confinement rigidity. A stiffness increase of 30% was witnessed in response to an 8% increase in initial density, while the stress–strain response of specimens confined via steel was noticeably stiffer than that of polycarbonate and polyolefin. Luo et al. [11] further

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quantified the increase of stiffness as a function of dry density via SHPB testing on dry sand with five densities ranging from 1.51 g/cm^3 to 1.75 g/cm^3. A power law relationship predicting the stress–strain response for any given initial sample density was then proposed. Further analyses of dry sand with densities of 1.51 g/cm^3, 1.63 g/cm^3 and 1.75 g/cm^3 for strain rates between 610 s^{-1} and 675 s^{-1} by Lu et al. [12] confirmed a stiffening of stress–strain behavior with increasing initial density under effectively uniaxial strain conditions. Different confinement environments were considered by Lu et al. [12] to assess their influence on the dry stress–strain response. Cylindrical sleeves made of polyvinyl chloride (PVC), polycarbonate, aluminum, and steel offered a maximum confinement pressure of 135 MPa. At strain rates ranging from 610 s^{-1} to 710 s^{-1}, an increasing lateral rigidity generated higher specimen stiffness with sand in the steel tube producing the stiffest response, and that in PVC exhibiting plastic behavior. SHPB experiments by Semblat et al. [13] further confirmed the observation that higher levels of confinement led to stiffer dynamic stress–strain response of dry sands under high strain rates. This phenomenon is thus attributed to the activation of increased frictional resistance between sand particles by amplifying the overall stress environment within the specimen [14]. Conversely, a lack of confinement rigidity leading to a softening response at a lower axial stress level can be observed while approaching shear failure. The crushing behavior of dry quartz sand under dynamic conditions was examined by Huang et al. [15]. Analyses of the particle size distribution after SHPB testing categorized the overall response into initial compaction, crushing, and crushing and compaction stages. Relationships between the transmission coefficient and wave amplitude were subsequently characterized for each deformation stage. Additionally, Xia et al. [16] explored the dynamic behavior of crushed rock particles from mine tailings via the SHPB to depict the phenomenon of acoustic fluidization in granular materials. It was revealed that samples 8 mm thick exhibit shear strength ten times that of their thinner counterparts, signifying the transition between solid and fluidized behavior. A fluidized response was also obtained for specimens examined below an impact velocity of 12 m/s.

In addition to the high strain rate characterization of dry sands, SHPB experiments have also been implemented on partially saturated specimens, albeit to a more limited extent. Veyera [17] conducted standard SHPB tests 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 an increasing moisture content ultimately resulted in water lock-up phenomena at lower strains (water lock-up is defined as the state at which the sample stress–strain behavior approaches that of pure water under dynamic uniaxial strain compression). 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. More recently, Martin et al. [18] 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 were more compliant than their dry counterparts 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 [18]. Wang et al. [19] further evaluated the influence of saturation, strain rate, and grain shape on the compressive stress–strain response and grain crushing of partially saturated beach sand confined in a rigid steel sleeve. It was found that the presence of moisture potentially renders specimens sensitive to changes in the strain rate, a phenomenon not typically observed in dry sand [9,10,13,14,20–22]. SHPB investigations by Lin et al. [22] on Ottawa sands of differing particle distribution further reinforced the strain rate dependent nature of highly saturated sands. This behavior was attributed to the stiffness and load bearing capacity of pore water under dynamic conditions.

Evidently, past studies into the dynamic response of sand have proven instrumental in providing insight on the mechanical behavior of such materials under various conditions. The parameterization of initial dry density and confinement environment in the context of SHPB experimentation was effective in exploring the basic mechanisms governing the impact compressive response of dry granular media. The subsequent introduction of moisture allowed for the observation of partially saturated behavior both before and after the initiation of water lock-up phenomena as a function of saturation [17–19]. The feasibility of numerical techniques in simulating the response of partially saturated sand was recently highlighted by Flores-Johnson et al. [1] via finite and discrete element modeling. However, substantially more work is required in order to further our understanding into the dynamic behavior of sand, particularly under the partially saturated regime. To date, little work has been done in investigating the effect of saturation on the high strain rate response of sand at various initial dry densities and confinement levels. This is attributed to the fact that the majority of partially saturated SHPB tests being performed on the specimens exhibit only a single density confined via steel chambers, thus restricting the extraction of results from the uniaxial strain response [10,17,18,23–25]. Additionally, very limited data are available in current literature pertaining to the energy absorption of sand under high strain rate loading conditions [26]. The quantification of grain crushing in relation to initial dry density and confinement rigidity in terms of water saturation is also an infrequently explored topic. Additional research is therefore required to systematically target the effect of initial dry density and confinement on the dynamic stress–strain behavior, energy absorption, and extent of particle breakage of sand as a function of saturation.

This paper aims at characterizing the compressive dynamic stress–strain response of a poorly graded fine-grained sand tested via the SHPB in order to address the deficiencies in existing literature surrounding the influence of confinement rigidity and initial dry density on the high strain rate response of partially saturated granular media. The primary task is to determine the stress–strain behavior and energy absorption of Stockton Beach sand at three initial dry densities, utilizing confinement chambers made of steel and polycarbonate, as a function of saturation. The implementation of pulse shaping allows dynamic stress equilibrium and constant rate deformations to be achieved, which makes possible the extraction of valid SHPB results. In addition, Hardin's relative breakage potential index is applied to evaluate the extent of particle breakage in the specimens retrieved post-impact. Experimental observations will therefore enable a systematic analysis of the factors affecting the high strain rate response of partially saturated sand. This acts to ultimately aid the development and validation of constitutive models applicable to the dynamic characterization of such materials.

2. Experimental and material characteristics

2.1. SHPB configuration

The SHPB is commonly used for characterizing the response of engineering materials to high strain rates [27], including soft porous materials such as sand and clays [14,28]. Conceptualized by Hopkinson [29] and refined by Kolsky [30], 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 thus propagating a compressive stress wave through the pressure bars and specimen. Due to the dynamic impedance mismatch between the sample and pressure bar, a portion of this compressive pulse is reflected at the specimen-incident bar interface as a tensile wave bouncing back towards the impact end of the incident bar, while the remaining pulse is