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Fractal crushing of carbonate and quartz sands along the specimen height under impact loading

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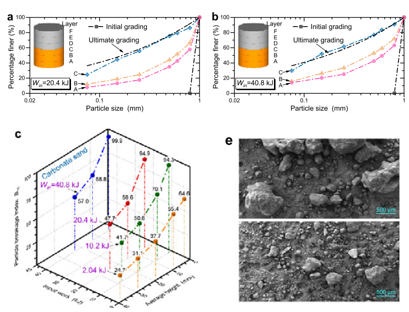
HIGHLIGHTS

- Carbonate sand exhibited more displacement than quartz sand.
- Grain crushing is inhomogeneous along the specimen height.
- Carbonate sand undergoes more particle breakage than quartz sand.
- Quartz sand exhibits more diverse along the specimen height than carbonate sand.

GRAPHICAL ABSTRACT



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ABSTRACT

Particle breakage is a significant phenomenon in civil, transportation and mining engineering. In this study, the evolution of the particle size distribution (PSD) and that of particle breakage of an overall sample and along the specimen height were systematically investigated via a series of impact loading tests for two sands: a carbonate sand (CS) and a quartz sand, i.e., Fujian sand (FS). The test results on the overall sample showed that the CS sample exhibited more changes in void ratio than the FS sample. In addition, the increase in the breakage extent in the overall CS sample at the initial loading stage was greater than that in the overall FS sample, and the final breakage extent in the overall CS sample was 45.8% larger than that in the overall FS sample. The PSD curve in an effective layer for the CS sample or FS sample broadened compared with that in the substratum effective layer, implying that the particle breakage was inhomogeneous along the specimen height. The CS or FS in the topmost effective layer beneath the hammer reached its corresponding ultimate fractal gradation, whereas the CS or FS in the lower layers presented values below the ultimate fractal gradation. Furthermore, the PSD and grain crushing distributions were more inhomogeneous along the FS sample than the CS sample.

1. Introduction

Particle breakage is a phenomenon that occurs when particles of granular soils are exposed to considerable stress or shear strain and then break into smaller-sized particles [1–4]. This phenomenon is commonly encountered in civil, transportation and mining engineering, such as in rockfill fractures in high dams [5–8], sand breakage induced by pile driving [9–12], railway ballast fractures under dynamic loading [13–16], sand crushing during ground improvement by dynamic compaction [17], and coal comminution [18,19]. In recent decades, a series of studies have performed laboratory tests and numerical analyses to investigate the

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Nomenclature

B_{15}, B_{10}, B_g, B_f and B_{r50}	single-number breakage index	h_a	average height (Unit: mm)
B_r, B_{rE}, I_G and BBI	area-ratio breakage index	e_{max}	maximum void ratio
B_{rE}	relative breakage index	e_{min}	minimum void ratio
B_p	breakage potential (Unit: mm)	e_0	initial void ratio
B_t	total breakage (Unit: mm)	e_u	ultimate void ratio
d	particle diameter (Unit: mm)	e	void ratio
d_M	maximum particle diameter (Unit: mm)	ρ_d	dry density of sand sample (Unit: g/cm^3)
d_m	minimum particle diameter (Unit: mm)	ρ_w	density of water (Unit: g/cm^3)
F	percentage finer (Unit: %)	v_s	volume of sample (Unit: cm^3)
α	fractal dimension	m_s	mass of sample (Unit: g)
W_{in}	input work (Unit: kJ)	r_s	radius of sample (Unit: mm)
m_h	weight of the hammer (Unit: g)	h_s	height of sample (Unit: mm)
h_h	height of hammer lifted (Unit: mm)	γ_B	fitting parameter
g	acceleration of gravity (Unit: m/s^2)	χ_W	fitting parameter
n_b	blow number	R^2	square of correlation coefficient
G_s	specific gravity		
D_r	relative density		
h_0	initial specimen height (Unit: mm)		

evolution of particle breakage of granular soils, such as one-dimensional compression tests [20–25], conventional triaxial tests [14,16,26–30], ring shearing tests [1,3], multiaxial tests [31], impact tests [32,33], cyclic tests [34,35], and discrete element method (DEM) modeling [36–42]. These studies have shown that the particle size distribution (PSD) could be changed due to fractures, attrition and abrasion of original grains [20]. Particle breakage exhibits a considerable influence on the mechanical behaviors of granular soils, including the stiffness [34], strength [34,43,44], dilatancy [7,45,46], thermal conductivity [47], and critical states [20,48–51]. The main parameters influencing the particle breakage of granular soils are grading [1,23,52], particle size [6,52,53], particle shape [54,55], individual particle strength [5,53], external stress [56–58], stress path [31,45,59], and saturation [60,61]. As reported by many investigators [62–65], the ultimate grading could be fractal, which can be described as follows:

$$F(d) = \left(\frac{d}{d_M}\right)^{3-\alpha} \tag{1}$$

where d is a particle diameter; d_M is the maximum particle diameter; F is the percentage of particles finer than d; and α is a fractal dimension. The ultimate fractal dimension for soils is 2.5, which is based on theoretical breakage studies [66–68]. However, the test results show that the ultimate fractal dimension of carbonate sands changes with the loading conditions; for example, α = 2.21–2.43 in one-dimensional compression tests [66], α = 2.57 in ring shear tests [3], and α = 2.63 in impact loading tests [69]. Specifically, Coop et al. [3] marked the specimens in ring shearing tests as Zone 1, Zone 2, and Zone 3 for the upper, central, and lower parts, respectively. The particle breakage in Zone 1 and Zone 3 is significantly smaller than that in Zone 2. Additionally, the fractal dimension of sand specimens after impact loading depends on the specimen height [42,69]. Moreover, the distribution of grain crushing along the central line under the end of the driving pile differs greatly [9,10,41,70]. Therefore, the extent of particle breakage and the ultimate fractal dimension of the sand samples depend not only on gradation, particle shape, external stress, test methodology, and mineral composition but also on the location within the specimen. However, the PSD evolution, particle breakage, and fractal characteristics of granular soils with different minerals along the specimen height under impact loading have not been previously investigated.

The aim of this study is to investigate the grain crushing and PSD evolution of carbonate and quartz sands along the specimen height after impact loading. The average grain crushing in an overall sample is also introduced for comparison with the grain crushing distributions along the specimen height. Comparisons of the grain crushing distributions along the specimen height between carbonate and quartz sands are also presented. The current research could be applied in the engineering field, such as for pile driving engineering and estimating the distributions of deformation and grain crushing.

2. Materials and test methods

2.1. Materials

The two types of sand used in this study are Fujian sand (FS), produced from Fujian Province of China, and carbonate sand (CS) obtained from the East Beach of China. Fig. 1 shows that the initial PSDs of the sands are equivalent and uniformly graded (0.8–1 mm). The optical microscope images in Fig. 1 illustrate that the FS is typical quartz sand with subrounded particles and smooth surfaces, and these characteristics are similar to Ottawa sand [71,72], Leighton Buzzard sand [73], and Toyoura sand [74,75]. In contrast, the CS in this research possesses angular grains with intraparticle porosities and rough surfaces, and these characteristics are similar to Dog's Bay sand [76], Barry's Beach sand [1], and Yongshu sand [77]. The material characteristics of both sand types are listed in Table 1. All sand samples used in the experiment have the same relative density of 79.9%.

2.2. Experimental apparatus

Impact compression tests are conducted via an automatic impact apparatus. As shown in Fig. 2a, this apparatus mainly consists of a switch, system timer, conveyor belt, guide rod, positioning block, lifting control sheet, hammer, hammer seat, fixator, and locking plate. The engine drives the conveyor belt up when the apparatus

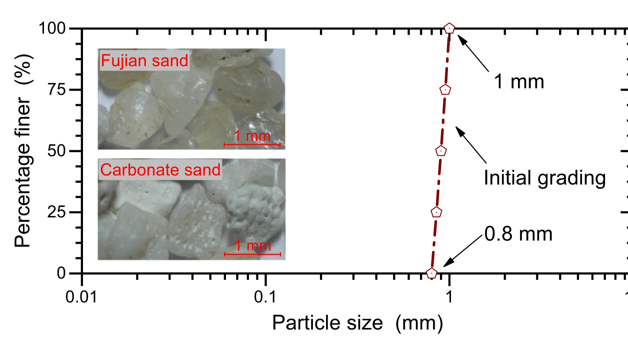

Fig. 1. Initial particle size distribution of the sand samples and optical microscope images of sand particles.