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Stress attenuation and energy absorption of the coral sand with different particle sizes under impacts †

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Abstract: The attenuation of stress wave and energy absorption in the coral sand were respectively investigated in this study. A series of experiments were carried out by using a new methodology with an improved split Hopkinson pressure bar (SHPB). Four kinds of coral sand, i.e., particle sizes of 1.18-0.60mm, 0.60-0.30mm, 0.30-0.15mm, and 0.15-0.075mm, are carefully sieved and tested. Significant effects of coral sand on attenuation of stress wave and energy absorption are observed, where, the correlation between the stress wave attenuation and energy absorption of coral sand is also validated. A similar conclusion was drawn on stress wave attenuation and energy absorption from the test results. There exists a common critical stress zone for the sieved coral sands, when the stress below this zone, sand with small particle size attenuates more stress wave and absorb greater energy; when the stress beyond this zone, sand with greater particle size behaves better on stress wave attenuation and energy absorption.

Keywords: coral sand; particle size; stress wave attenuation; energy absorption; SHPB

1. Introduction

Sand is the commonly used material in engineering construction, which attributes to its easy availability and cheapness. In addition, the remarkable ability on stress wave attenuation and energy absorption make sand the most appropriate material on blast mitigation and vibration isolation. Coral sand is widely distributed in the marine environment between 30 degrees north latitude and 30 degrees south latitude. Different composition and granular structure from the terrigenous sand (such as silica sand) make the coral sand behaves better on stress wave attenuation [1].

The mechanisms of propagation and energy absorption of the stress wave in sand is mainly determined by its physical and mechanical properties. Some published literatures [2, 3] demonstrated that the particle size exhibits significant influence on the physical and mechanical properties of sand, such as density, porosity, elastic modulus, yield stress, and compressibility. Therefore, a study on the effect of particle size of coral sand on stress wave attenuation and energy absorption is meaningful for design and construction of marine engineering.

To study the effect of particle size of coral sand under impact loads, experiments for coral sand on stress wave attenuation and energy absorption are respectively designed and performed. The results of both experiments are analyzed and compared, and a similar conclusion on the effect of particle size are drawn.

2. Materials and Methodology

2.1. Coral sand

The as-received coral sand is wet with strong fishy smell. The sand is firstly dried in the drying oven at 105℃ for 24 hours, and then sorted by the standard sieves and a vibrating screen machine [4]. Four kinds of dry coral sands with particle sizes of 1.18-0.60mm, 0.60-0.30mm, 0.30-0.15mm, and 0.15-0.075mm, as shown in Figure 1, are tested under impact through SHPB. The coral particles owns angular appearance which contains numerous micro-holes and cavities. The specific gravities (G_s) and the maximum & minimum densities of four kinds of the coral sands are tabulated in Table 1. Good agreements on G_s with previous studies, 2.88 of Lade et al [5] and 2.82 of Lv et al [6], show the validity of the data. In the following impact tests, all the specimens of four kinds of coral sand are assembled by the relative density of 0.5.

(**a**) (**b**) (**c**) (**d**)

Figure 1. Coral sand with different particle sizes: (**a**) 1.18-0.60mm (**b**) 0.60-0.30mm; (**c**) 0.30-0.15mm; (**d**) 0.15-0.075mm.

Table 1. Initial physical parameters of coral sand.

	1.18-0.60mm	**0.60-0.30mm**	**0.30-0.15mm**	**0.15-0.075mm**
Specific gravity	2.792	2.804	2.803	2.814
Maximum density(kg/m³)	1142	1195	1257	1460
Minimum density(kg/m³)	1035	1092	1066	1153

2.2. Improved SHPB for stress wave attenuation

The improved SHPB for stress wave attenuation is consisted of a 0.8m striker, a 5m incident bar and a 4m transmission bar with a common diameter of 75mm. The low-mechanical-impedance technique, i.e. the hollow shape and aluminum material, is used to raise the accuracy of the results. The inner diameter and outer diameter of the bars are 50mm and 75mm, respectively. The rubber pulse-shapers are used to filter out the high-frequency pulse and elongate the rise time of the stress wave. The impact velocity of the striker is ~10m/s, which correspondingly generates stress wave with amplitude of ~5MPa at the front end of the specimen.

The confined "long" specimens, which long enough to prevent internal axial reflection of the stress wave during the experiment duration, with length of 75mm, 150mm, 225mm, and 300m are designed for the test. All the lengths are tested three times for cross calibration. The specimen is assembled by a length adjustable sleeve and two thin platens. The tubular sleeve is made of stainless steel with inner diameter of 75mm and outer diameter of 95mm. The cylindrical platens are made of high-strength aluminum with diameter of 75mm and height of 10mm.

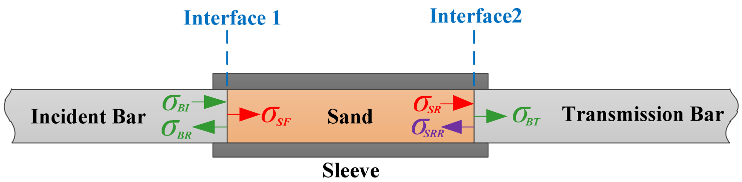


Figure 2. The stress wave transmits between the specimen and the bars.

The stress wave transmits between the specimen and the bars is shown in Figure 2. The peak stress of the stress wave at the front end of the specimen $\sigma_{SF-peak}$ is calculated by

$$\sigma_{SF-peak} = \sigma_{BI-peak} + \sigma_{BR-peak} \tag{1}$$

where $\sigma_{BI-peak}$ and $\sigma_{BR-peak}$ are the peak stress of the incident wave and the peak stress of the reflected wave.

The peak stress of the stress wave at the rear end of the specimen $\sigma_{SR-peak}$ is calculated from [7]

$$\sigma_{SR\text{-}peak} = \sigma_{BT\text{-}peak} / T_2(\sigma) \tag{2}$$

where $\sigma_{BT\text{-}peak}$ is the peak stress of the transmitted stress wave, σ equals to $\sigma_{BT\text{-}peak}$ at the interface 2; $T_2(\sigma)$ is the transmission coefficient of interface 2 which is obtained by the reflected coefficient of interface 1 $F_1(\sigma)$ through relation [8]

$$F_1(\sigma) + T_2(\sigma) = 1 \tag{3}$$

$F_1(\sigma)$ is fitted by experimental data of $\sigma_{BI-peak}$ and $\sigma_{BR-peak}$ from relation

$$F_1(\sigma) = \sigma_{BR-peak} / \sigma_{BI-peak} \tag{4}$$

where σ is equal to $\sigma_{SF-peak}$ at interface 1, as express by equation (1).

Therefore, the non-dimensional peak stress of stress wave *D* for certain length of the specimen could be calculated

$$D = (\sigma_{SR-peak} / \sigma_{SF-peak}) \cdot 100\% \tag{5}$$

2.3. SHPB for energy absorption

The SHPB for energy absorption contains a 0.8m striker, a 6m incident bar and a 3.5m transmission bar with a common diameter of 20mm. The material of the bars is high-strength aluminum. The rubber pulse-shapers are used to filter out the high-frequency pulse and elongate the rise time of the incident pulses for stress equilibrium of the specimen. The impact velocity of the striker is ~10m/s, which correspond to a peak stress of ~15MPa in the specimen.

The diameter and thickness confined specimen are 20mm and 10mm. The specimen is assembled by a sleeve and two thin platens, which are made of stainless steel. The tubular sleeve has an inner diameter of 20mm and an outer diameter of 26mm. The cylindrical platen has a diameter of 75mm and a height of 10mm.

The experimental data is processed through two-wave method, the stress equilibrium of the specimen is firstly verified by

$$\varepsilon_i(t) + \varepsilon_r(t) = \varepsilon_t(t) \tag{6}$$

where $\varepsilon_i(t)$, $\varepsilon_t(t)$ and $\varepsilon_r(t)$ are incident wave, transmitted wave, and reflected wave, respectively.

Then the stress, strain rate, strain histories of the specimen can be calculated from equation (7)-(9) [9]

$$\sigma(t) = E_0 \varepsilon_t(t) \tag{7}$$

$$\dot{\varepsilon}(t) = -2\frac{C_0}{L_S}\varepsilon_r(t) \tag{8}$$

$$\varepsilon(t) = -2\frac{C_0}{L_S}\int_0^t \varepsilon_r(t)dt \tag{9}$$

where E_0 and C_0 are Young's modulus and elastic wave velocity of the bar material, respectively; L_S is length of the specimen.

The absorbed energy by the granular material per unit volume can be obtained from the integration of the stress-strain curves through equation (10)

$$W = \int_0^{\varepsilon} \sigma d\varepsilon \tag{10}$$

3. Results and Discussion

The non-dimensional peak stress of four kinds of coral sand at different distances are shown in Figure 3, every symbol represents an available individual experimental data. The stress wave is attenuated significantly in the coral sand, which agrees well with the previous investigation [1]. At the distance of 75mm, coral sands of 1.18-0.60mm, 0.60-0.30mm, 0.30-0.15mm, and 0.15-0.075mm, attenuate the stress wave to ~30%, ~30%, ~35%, and, ~46% respectively. Specimens of larger particle sizes attenuate stress wave faster in this distance. At the distance of 150mm, coral sands of four particle sizes share a similar non-dimensional peak stress ~15%. *D* of specimens of smaller particles catch up with the larger ones at this distance. At the distance of 225mm, *D* of smaller particle sizes specimens surpass the larger ones. Coral sands of 1.18-0.60mm, 0.60-0.30mm, 0.30-0.15mm, and 0.15-0.075mm, attenuate the stress wave to ~8%, ~7%, ~6%, ~5%, respectively. Similarly, specimens of smaller particles attenuate stress wave better at distance of 300mm, where the coral sands of 1.18-0.60mm, 0.60-0.30mm, 0.30-0.15mm, and 0.15-0.075mm, attenuate the stress wave to ~5%, ~4%, ~3%, ~2.8%, respectively.

The aforementioned phenomenon should be derived from the intrinsic mechanical properties of four different coral sands. It is reasonable to assert that there is a critical stress (a point or a range of zone) when stress wave propagates in the range of 75-150mm. The attenuation mechanisms of the sands of all sizes reverse at the critical stress. At distance of 75mm, the maximum measured $\sigma_{SR-peak}$ of four sizes of sands is 1.98MPa; and at distance of 150mm, the minimum measured $\sigma_{SR-peak}$ of four sizes of sands is 0.39MPa. Therefore, the critical stress should be in range of 1.98-0.39MPa.

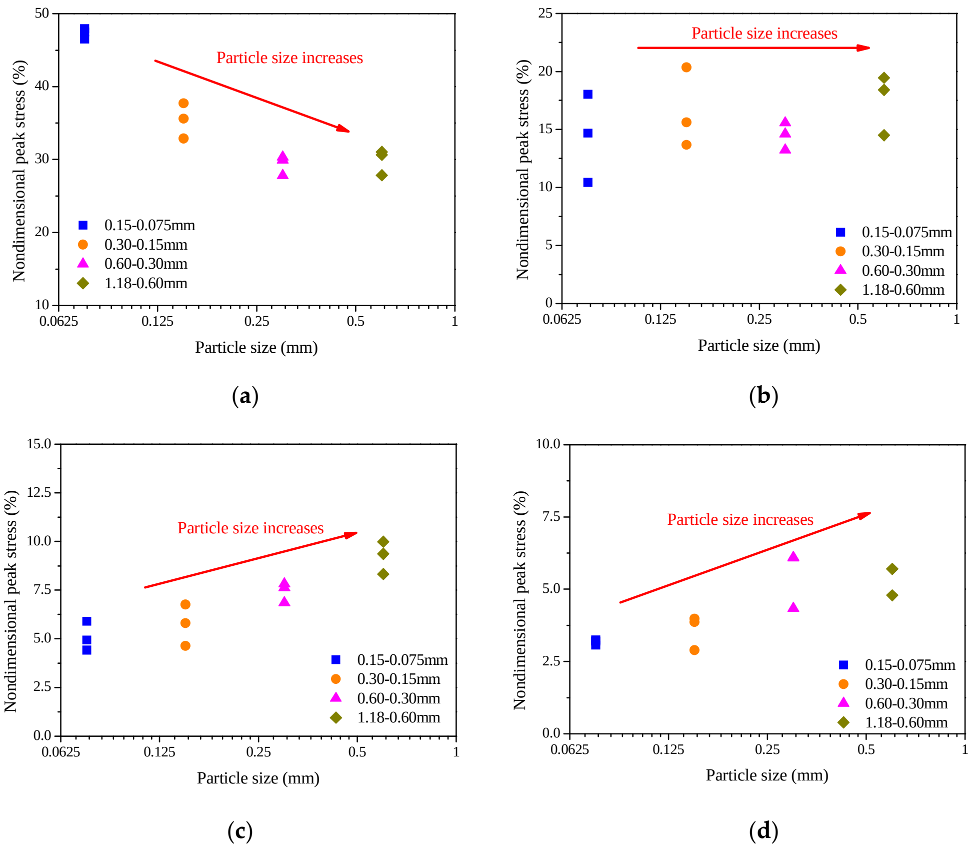
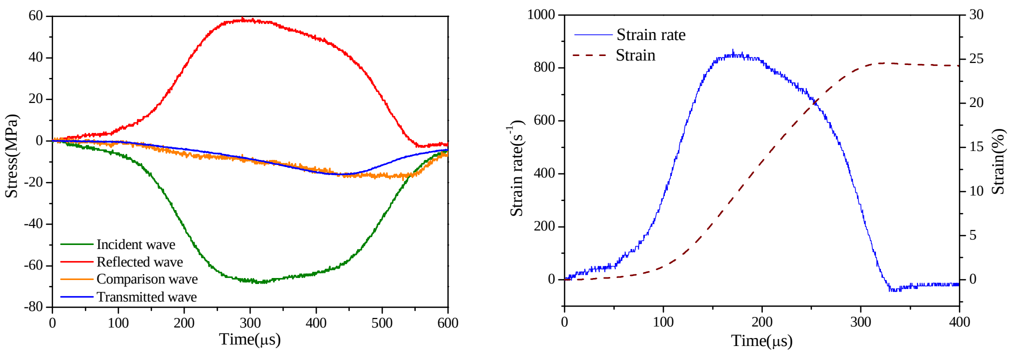


Figure 3. Peak stress attenuation of coral sand with different particle sizes at different distances. (**a**) 75mm; (**b**) 150mm; (**c**) 225mm; (**d**) 300mm.

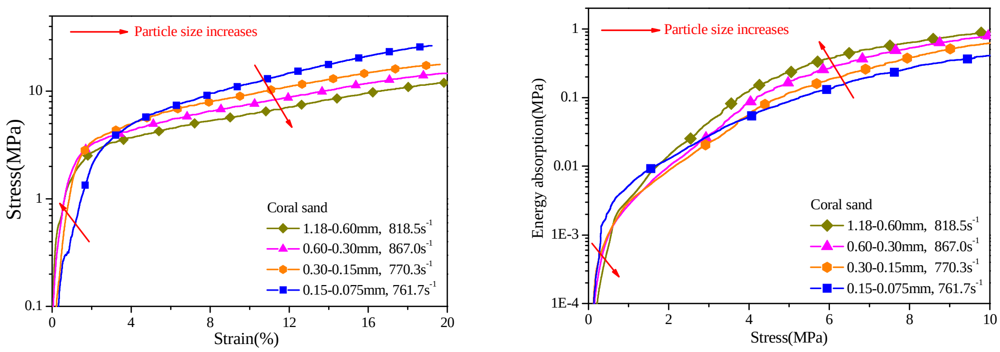
A typical set of stress waves of the energy absorption experiment is shown in Figure 4 (a). Benefit from the pulses shaping technique, the incident wave with a rise time about 300μs is generated. The long rise time of the incident pulse makes the stress in the specimen in equilibration, as shown of the nearly overlapped "comparison wave" and "transmitted wave" in Figure 4 (a). The strain-rate history and the strain history are shown in Figure 4 (b), the strain rate is nearly a constant (800/s) from ~150 to 250μs that correspond to the strains from 5% to 20%. Therefore, the specimen is deformed uniformly at the nearly constant strain rate, resultant of the stress-strain curve is validated.

The stress-strain curves and energy absorption curves for coral sand with different particle sizes are shown in Figure. 5 (a) and Figure 5 (b), every curve is averaged from three experiments. The particle size has a significant effect on the compressive behavior and the energy absorption. A clear critical zone in the range of 3.93-0.59MPa, which covers the yield stresses of the four different coral sands, can be observed in the Figure. 5 (a). This critical zone is very close to that of 1.98-0.39MPa for stress wave attenuation. When the stress below the critical zone, larger sand particles tend to carry higher stress and deform less, which cause the specimen absorb less energy in macro-scale. This phenomenon in low stress agrees with the stress wave attenuation at distance of 225mm and 300mm, as shown in Figure. 3 (c) and (d). When the stress beyond the critical zone, the curves shift upside down. To the right of the critical zone, the stress-strain curves for smaller size sand shift upwards, indicating that smaller size particles carry higher compressive stress than that of the larger sand particles; the energy absorption curves for smaller size sand shift downwards, indicating that specimens of smaller particles absorb less energy than that of the specimens of larger particles. The stress beyond the critical zone correspond to the stress wave attenuation at distance of 75mm, as shown in Figure. 3 (a). Therefore, the similar results indicate stress wave attenuation and energy absorption of coral sand are correlated.



(**a**) (**b**)

Figure 4. Typical stress equilibrium and strain & strain-rate histories for a coral sand specimen with particle size 1.18-0.60mm. (**a**) Stress equilibrium; (**b**) Strain & strain-rate histories.



(**a**) (**b**)

Figure 5. Stress-strain curves and energy absorption curves for coral sands with different particle sizes. (a) Stress-strain curves; (b) Energy absorption curves;

4. Conclusion

The stress wave attenuation and energy absorption for coral sand with different particle sizes under impact loads are investigated. The clear correlation or connection between the stress wave attenuation and the energy absorption is observed and validated. A common critical stress zone (1.98-0.39MPa for stress wave attenuation, 3.93-0.59 for energy absorption) for four kinds of coral sands exists. Coral sands of smaller particle sizes sustain lower stress and deform more when stress below the critical stress zone, that eventually benefit better performance on stress wave attenuation and energy absorption. On the contrary, coral sands of larger particle sizes bear lower stress and deform more when stress beyond the critical stress zone, that eventually benefit better performance on stress wave attenuation and energy absorption.

It should be noted that the effects of stress wave attenuation and energy absorption in the coral sand also depends on the length of impulse, which should be carefully studied with intensive tests in the future.

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Author Contributions: Q.F., L.C. and X.Y. conceived and designed the experiments; X.Y. performed the experiments; X.Y. analyzed the data; W.C. contributed analysis tools; X.Y. and L.C. wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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