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Propagation of shock waves in dry and wet sandstone: Experimental observations, theoretical analysis and meso-scale modeling

Chuang Liu [a], Yang Wu [b], Xian-feng Zhang [a, *], Jia-jie Deng [a], Chen-yang Xu [a], Wei Xiong [a], Meng-ting Tan [a]

[a] School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing, Xiaolingwei 200, Nanjing, China
[b] NO.208 Reseach Institute of China Ordnance Industries, Beijing, China

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Methods of experimental observations, theoretical analysis and meso-scale modeling were used to study the propagation processes of shock waves in dry and wet sandstone under dynamic impact in this paper. According to the results from the dynamic impact experiments with velocity of 0.2–0.5 km/s, it was found that the velocity of shock wave increases linearly with water content. Additionally, the velocity of the shock wave in the sandstone showed a linearly increased regularity with the increasement of the impact velocity, which was proved by theory in this paper. Furthermore, meso-scale simulation models were performed and the simulation results showed that sandstone's porosity reduced the shock waves velocity compared to nonporous materials. Pore space filled with water counteracts the effects of porosity, resulted in larger shock wave velocity.
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1. Introduction

Porosity and water content are typical properties for sandstones of the upper crust of Earth such as sandstone, which is comprised of one or more mineral composition with a certain texture and structure of aggregates. Sandstone structurally has a lot of defects which makes it classified as heterogeneous, discontinuous and anisotropic. And it is the same with numerous planetary. Planetary materials have high amount of empty pore space and porosities of some of them up to 75% (Britt et al., 2002 [1]), the water content are deferent between planets. The analysis of shock waves propagation into wet and dry porous materials is necessary in order to have a better understanding of dynamic destruction processes on these types of planetary materials. Thereby we can have a clearer insights about the mechanisms of subsurface damage and effect of porosity and water content on sandstone fracture and deformation.

For a better understanding of the multiple processes occurring in meteorite impacts, the MEMIN (Multidisciplinary Experimental and Modeling Impact Research Network) (Poelchau et al., 2013 [2], Hoerth et al., 2013 [3], Sommer et al., 2013 [4], Dufresne et al., 2013 [5], Güldemeister et al., 2013 [6], Buhl et al., 2013 [7]) apply different methods, in particular, studying the natural craters and performing laboratory experiments and numerical simulations. They analyze the cratering shape, ejecta cloud and propagation of shock waves of wet and dry porous materials. Impact cratering experiments were carried out in porous sandstones which showed that pore with have great of influence for shock wave velocity and cratering volume (Kenkmann et al., 2011 [8]). Hypervelocity impacts on dry and wet sandstone were studied by using meso-scale simulations to understand the influence of porosity on the mechanical behavior of sandstone (Durr et al., 2013 [9]). Baldwin et al. (2007 [10])studied the macroscopic response of sandstone with different microscopic characteristics under hypervelocity impact by scaling impact cratering experiments and determined give the equation of state. Buhl et al. (2013 [11]) investigated the particle size distribution and strain rate attenuation in hypervelocity impact and shock recovery experiments. Kirk et al. (2014 [12]) studied the Hugoniot of two geological materials, namely Lake Quarry Granite and Gosford Sandstone by a series of plate impact experiments using a 50.8 mm smooth bore single stage light gas gun. Miljkovic et al. (2007 [13]) combined sandstone flyer plate impact test data with high pressure quartz data to produce a synthetic Hugoniot. Chapman et al. (2006 [14]) performed a series of plate impact experiments on quartz sand of 230 μm average grain size, at various levels of water saturation to obtain Hugoniot data,

* Corresponding author.
E-mail address: lynx@njust.edu.cn (X.-f. Zhang).
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Nomenclature

M_1	Initial mass of the dry sandstone
M_2	Mass of the water saturated sandstone
m_1	Mass proportion of air in rocks
d	Sandstone specimen diameter
h	Sandstone specimen thickness
v_1	Volume ratios of the gas
v_2	Volume ratios of the water
v_3	Volume ratios of the quartz
$\rho_{1,0}$	Initial density of the gas
$\rho_{2,0}$	Initial density of the water
$\rho_{3,0}$	Initial density of the quartz
ρ_0	Initial density of the sandstone
w_0	Initial ratios of the water
U_S	Shock velocity
U_P	Particle velocity
S_{m0}	Experience parameter
γ_{m0}	Gruneisen coefficient of matrix material
β_i	The mass of the percentages of the ith component
H_K	The coefficient of viscosity
K	Bulk modulus
m_3	Mass proportion of quartz in rocks
G_K	Shear moduli parameter 1
G_M	Shear moduli parameter 2
γ	Gruneisen parameter
S	The slope of the $Us-Up$ Hugoniot
V_{00}	Initial porous specific volume
V_0	The solid material specific volume
L_0	Sandstone specimen thickness
ε	The strain of matrix material
v_m	Volume of matrix material
p_m	Base material pressure
ρ_{m0}	Initial density of component of mixture
σ_1	Maximum principal stress
σ_2	Minimum principal stress
α	The material is characterized by the relative volume of voids
C_{m0}	The sound velocity of material with zero pressure

and high levels of water saturation were found to strongly influence the Hugoniot. Wang et al. (2010 [15]) performed impact compressive experiments on dry and wet sandstone conducted with modified Φ75 mm Split Hopkinson Pressure Bar (SHPB) apparatus; they found that water content can influence the damage patterns of sandstone and the impact damage of dry sandstone is more severe than that of wet sandstone. Ju et al. (2009 [16]) and Yu et al. (2011 [17]) studied the porous media stress wave propagation and change of the internal pores by SHPB shock compression tests and CT scanning electron microscope. Lou (1994 [18]) analyzed the dynamic fracture behavior of dry and waterlogged granites by SHPB experiments. Luo et al. (2012 [19]) presented relationship between macroscopic and meso-scale mechanical parameters of inhomogenous sandstone material by numerical simulation.

Apparently, the presence of water affects the dynamic damage characteristics, such as shock wave propagation and attenuation. In this article, We focused on quantifying the effects of dryness and wetness on shock wave propagation. And dynamic experiments were carried out to have a better understand of the deformation mechanisms associated with dry and wet sandstone. Also, based on a mixture of the superposition principle and the equation state of the porous material, theoretical model was established which can reflect the Hugoniot curve of porosity and pore space saturation of sandstones. Based on the electron micrograph of meso-structure of typical sandstone materials, simulation models of compressive processes of sandstone materials were conducted in meso-scale level with AUTODYN@ software. Also, the influences of different porosity and water content on the impact compression properties of sandstone materials were studied by meso-scale simulation models built in this article. Finally, some interesting conclusions about the effect of microscopic model on shock wave velocity in rocks are obtained through experiments, theoretical and simulation analysis.

2. Experiments

2.1. Sample preparation

In order to obtain the influence of water content ratio properties on shock wave propagation, Yellow Sandstones impact Experiments were carried out. The bulk density of the Yellow Sandstone was $2.20 \pm 0.04\,g\,cm^{-3}$, which was determined by scaling the weights and volumes of dried sandstone samples. Additionally, the porosities of the sandstones were calculated for six dry samples with an average value of 20%.

In order to reduce the influence of sparse waves at the boundary on the Yellow Sandstone sample, the sample size was set as Φ 50 mm × 8 mm. The photographs of the Yellow sandstone samples are shown in Fig. 1. The preparation process of samples is described as follows:

(1) Preparation for dry Yellow Sandstone samples. The initial Yellow Sandstone samples were placed in the electric thermostatic drying oven at a constant temperature of 40–60 °C for 48 h. The weights of the samples M_1 were measured after drying, which are listed in Table 1.
(2) Preparation for water saturated Yellow Sandstone samples. Part of dry sandstones were saturated in a chamber with water for two weeks. During this period, air bubbles were released from the water and the water saturations reached approximately to 80%. The photograph of the water saturated Yellow Sandstone is shown in Fig. 2. The weights M_2, diameters d, thickness h, as well as water saturations were listed in Table 1.

2.2. Launcher and flyer plates

The sabot, with a shear ring at one end to control the initial velocity of the flyer plate, was made of aluminum 2A12, as shown in Fig. 3. To eliminate the disturbance of the reflected waves produced in the impact process, the head portion closed to the flyer plate in the sabot was hollow. Furthermore, copper, with density of $8.92\,g\,cm^{-3}$, was selected as the material of flyer plates. And the accelerator in the experiments is shown in Fig. 4.

2.3. Experiments components

The PVDF piezoelectric film sensors with insulating treatment were pasted on the center surfaces of the sample. Also cover plates were designed in the test components, in order that we can obtain accurate and stable shock wave data, as shown in Fig. 5. The cover

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