Experimental Study on Impact Failure Characteristics of Large-size Boulder Specimen by SHPB

Jinguo Cheng¹, *, Hua Jiang¹, Xingfei Jiao², Yusheng Jiang¹, Jiachen Zhu¹

¹ School of Mechanics and Civil Engineering, China University of Mining and Technology, Beijing 100083, China.
² Shandong Provincial Architecture Design & Research Institute Co., Ltd, Jinan 250001, China.

*Corresponding author email: chengjinguo1991@student.cumtb.edu.cn

Abstract. The issue of rock breaking is inevitable when shield excavating the strata rich in boulders with large size. Based on the one-dimensional elastic stress wave theory, the dynamic stress-strain relationship of rock specimens under single impact and cyclic impact load is obtained by using split Hopkinson pressure bar test system, and the variation law of absorbed energy with the changes of impact pressure or impact frequency is analyzed. The experiment results indicate that under single impact, when the impact pressure is added, the peak value of strain and stress increase; the dynamic elastic modulus of the specimen increases in the elastic stage, while increases at first and then decreases in the non-linear elastic loading stage. Also, the optimal impact energy exists corresponding to the maximum absorbed energy. Under the cyclic impact, the rock failure needs to meet the requirement of lowest impact energy. With the increase of impact pressure, the peak strain and single absorbed energy decrease at first and then increase, and the cumulative absorbed energy increases gradually. When the impact energy exceeds the energy required for rock failure, the rock is subject to primary impact failure. The research results can provide reference for the design of rock breaking cutters and the control of shield tunnelling parameters.

Keywords: large size boulder; rock impact breaking; SHPB experiment; impact frequency; absorbed energy.

1. Introduction
Shield tunnelling generally encounters sand gravel strata rich in large-size boulders in some cities such as Beijing and Chengdu, which brings great difficulties to the cutter breaking rock, cutter wear and tunnelling parameter control. This kind of strata is characterized by high content of boulder, large size, high strength and strong abrasion [1-2]. The large-size boulder is difficult to be quickly broken by conventional cutters, which may seriously affect the efficiency of shield tunnelling. Such construction problems caused many researchers to carry out relevant theoretical and experimental research. Hertz (1961) [3-4], Paul Sikasskie (1965) [5], Dutta (1972) [6], Ozdemir et al (1979) [7] have studied the rock breaking model and mechanism and formed the perfect rock breaking theory. Zhang zhaohuang (1995) [8] established the rock breaking process and proposed the rock breaking force of disc cutter. Wu Qixing
2 (2011) [9] carried out mechanical analysis on rock breaking of disc cutter based on dimensional analysis theory. Xu Xiaoh, Afrouz, Giacomin et al. studied the basic theory and research methods of rock breaking and made great contributions to crack propagation and energy analysis [10-12]. Hopkinson (1914) [13] invented the Hopkinson pressure bar through experience innovation, and then Kolsky [14] improved the device and successfully invented the split Hopkinson pressure bar (SHPB), which is mainly used to study the dynamic characteristics of rocks. Guo Lianjun [15], Deng Yong [16] and Jin Jiefang [17] studied the mechanical properties, energy dissipation characteristics, failure mode of rock under different impact conditions by using SHPB test and summarized the dynamic change characteristics of rock.

In this paper, SHPB experiment is applied to study the dynamic mechanical characteristics of large-size boulder specimen under single impact and cyclic impact. The crushing process of specimens under different impact energy and impact frequency is analyzed based on the deduction of the rock dynamic stress-strain relationship and energy dissipation. Relevant research results are expected to provide certain guidance for cutter design and shield tunnelling control.

2. Research background

Generally, two situations occur when the shield applies heavy tearing cutters to break rock. One is the impact energy of tearing cutter large enough to crush the boulder instantly, and the other is too little impact energy carried by tearing cutter to crush the boulder in single impact and multiple impacts needed. Single impact to crush the boulder by tearing cutter is difficulty in practical engineering. The large-size boulder in soft strata are cyclically impacted by the cutters on the same track of the cutterhead, thus new cracks are generated and continue to develop until throughout the boulder, and then the boulder is broken. The study of single impact and cyclic impact of large-size boulders is of great significance to the research on rock breaking process by tearing cutter.

3. Principle and preparation for SHPB experiment

3.1. Basic Principle and Experimental Device

SHPB experiment is applied to study the impact failure characteristics of large-size boulder specimen. SHPB device is mainly divided into three parts: pressure bar system; measurement system; data acquisition and processing system, as shown in Fig. 1. The pressure bar system is composed of impact bar, incident bar, transmission bar and absorption bar. The experimental principle is described as follows: the impact bar collides with the incident bar and produces compressive stress wave. When the stress pulse in the incident bar reaches the contact surface with the specimen, part of the pulse is reflected and forms reflection wave in the incident bar; the other part enters into the transmission bar through the sample and forms transmission wave. Based on the time-varying pulse signals continuously recorded by the strain gauges pasted on the incident and transmission bars, the change process of the stress, strain and strain rate with time and the dynamic stress-strain relationship of the specimen are obtained by using the one-dimensional stress wave theory and the assumption of homogeneity, so as to deduce the variation characteristics of the absorbed energy. The calculation process can refer to the relevant literature [16].

Figure 1. Schematic diagram of SHPB experimental device.
3.2. Specimen Preparation and Mechanical Parameter Determination
The rock specimens used in the experiments are selected from the large-size boulders excavated from the shield tunnel of bid 6 in Beijing Subway Line 9. According to the experimental requirements, rock abrasion test (CAI), uniaxial compressive strength (UCS) test and Brazilian tensile strength (BTS) test were carried out to determine the mechanical parameters. The experimental process and results are shown in Fig. 2 and Table 1. The SHPB test was carried out using a standard cylinder with the length diameter ratio of 1:1 and the size of $\phi$ 50mm $\times$ 50mm (Fig. 2).

(a) rock specimen for SHPB (b) rock abrasion test (CAI) (c) UCS test (d) BTS test

Figure 2. Rock specimens and mechanical experiments.

### Table 1. Mechanical parameters of large-size boulder material.

| Material          | Density/g·cm$^{-3}$ | Modulus of elasticity/GPa | Poisson ratio | UCS/MPa  | BTS/MPa  | CAI |
|-------------------|---------------------|----------------------------|---------------|-----------|-----------|-----|
| large size boulder| 2.57                | 28.38                      | 0.26          | 134.75    | 4.57      | 3.32|

3.3. Design of Experimental Scheme
Two kinds of SHPB tests, single impact and cyclic impact, were carried out in this experiment. In single impact test, the impact bar can acquire different impact velocity and kinetic energy under different impact pressure by changing the impact pressure. The greater the impact pressure, the greater the impact energy. A total of ten different gradient pressures, i.e., 0.56 to 0.74 MPa (adjacent pressure difference is 0.02 MPa) are arranged. According to the single impact test results, five groups of impact pressure (0.56 to 0.64 MPa, adjacent pressure difference 0.02 MPa) were selected for cyclic impact test. The specimens were subjected to multiple impact tests under the same air pressure, and three parallel tests were conducted for each air pressure. The experimental data were recorded at the end of each impact, and the crushing conditions of the specimens were photographed and analyzed. SHPB device and dynamic loading diagram of specimen is shown in Figs. 3 and 4, respectively.

Figure 3. SHPB experiment device.  
Figure 4. Dynamic loading on rock specimen.
4. Failure characteristics of specimens under single impact

4.1. Analysis of Specimen Crushing Effect under Single Impact
No macroscopic crack can be identified by naked eyes within the impact pressure range of 0.60MPa, and the specimen basically has no change, as shown in Fig. 5. With the increase of impact pressure, small longitudinal cracks appear on the surface of the specimen but don't penetrate the whole specimen. Under the impact pressure of 0.70MPa, the specimen shows significant axial splitting failure and is broken into large pieces with complete fragments. When the impact pressure increases to 0.72 MPa, the specimen is seriously broken both along the longitudinal and transverse directions. The degree of fragmentation is significant, showing small pieces and poor integrity.

![Figure 5. Rock failure condition of single impact on specimen at different impact gas pressure(energy)](image)

4.2. Dynamic Stress-strain Relationship under Impact Loading
Figure 6 reflects that the dynamic stress-strain relationship curve presents four stages: compaction stage, elastic stage, non-linear elastic loading stage and unloading stage. With the increase of impact pressure, the stress-strain slope of elastic stage increases as well as the dynamic elastic modulus. During the non-linear elastic loading stage, the peak stress gradually increases when the impact pressure increases, and the dynamic elastic modulus of this stage increases first to the maximum value and then decreases.

4.3. Variation Characteristics of Energy
The information in Fig. 7 indicates that with the increase of impact energy, the incident energy, transmission energy and reflection energy all present a gradual increase trend, and the incident energy basically increases linearly, showing that the impact energy is proportional to the incident energy. The transmission energy and the reflection energy are basically the same under the lower level of impact energy. When the impact energy exceeds a certain value, the transmission energy tends to decrease while the reflected energy gradually increased. Figure 8 shows that the maximum absorbed energy of rock does not appear at the moment of the maximum incident energy. The absorbed energy of rock is also less and little change when the incident energy is lower, which indicates that the lower absorbed energy cannot make the rock broken into fragments. When the impact energy increases to a certain value, the rock absorbed energy increases gradually with great growth rate, reaches the maximum and then decreases gradually. Thus, the impact energy needs to obtain the optimal value in order to make the rock absorb the most energy.

![Figure 6. Stress-strain curve under different impact energy](image)

![Figure 7. Energy change curve with impact energy](image)
5. Failure characteristics of specimens under cyclic impact

5.1. Analysis of Specimen Crushing Effect under Cyclic Impact

Under the impact pressure of 0.56MPa, the specimen has no change after 20 times of cyclic impact, and the impact energy fails to reach the limit value of rock fragmentation and has no effect on the development of rock cracks. As show in Fig.9, under 0.60 MPa, slight longitudinal cracks appear initially and continue to develop and penetrate the specimen. Under 0.62MPa, obvious cracks occurs in the specimen at the first impact, develops obviously at the second impact, penetrates the specimen at the third impact and the specimen breaks at the forth impact with significant degree of fragmentation. When the impact pressure increases to 0.64 MPa, the specimen basically fractured at the first impact with serious fragmentation and many cracks. Also, the experiment reveals that with the increase of pressure gradient, the cycle frequency required for specimen failure decreases gradually.

5.2. Relationship between Rock Strain and Impact Frequency

According to the theory of rock strength, the tensile failure effect occurs when the rock reaches the ultimate strain. Hereby the dynamic strain change is mainly analyzed. Figure 10 indicates that the strain of the specimen is relatively small at the initial impact. With the increase of the impact frequency, the cumulative strain tends to decrease, which indicates that the pores of the specimen are compressed under the impact, and the strain difference of rock is relatively obvious. At a higher pressure level, the rock strain generally decreases first and then increases until it reaches the peak value. The higher impact pressure ensures the more energy output, and the larger of rock strain requires the less impact frequency.

5.3. Relationship between Absorbed Energy and Impact Frequency

Figure 11 shows the relationship between the absorbed energy and the impact frequency. The results indicate that the absorbed energy at the impact pressure of 0.56MPa is very little and nearly remain the same, which is the main reason for no obvious damage on the specimen. Under the pressure gradient of 0.58 MPa to 0.62 MPa, the absorbed energy of rock specimens decreases first and then increases. Figure 12 shows more intuitively that the rock failure requires the cumulative absorbed energy to a certain
threshold, which may increase slowly and even not induce the rock failure when the impact pressure is lower, while increase rapidly when the pressure level is great. Once the impact energy exceeds the rock failure energy threshold, one impact can break the rock directly. This may provide certain reference for the cutter design and tunnelling control when shield excavating similar stratum rich in large size boulders.

6. Conclusions
In this paper, the rock damage characteristics under single impact and cyclic impact are studied by SHPB experiments based on rock breaking issue in large-size boulder stratum, main conclusions are drawn as follows:

1. SHPB experimental system can be applied to obtain the dynamic stress-strain relationship of rock specimen under impact loading, and the study on the absorbed energy required for specimen failure with impact frequency may provide guidance for the investigation of rock breaking by shield cutter.

2. Under single impact, with the increase of impact pressure, the dynamic elastic modulus of the specimen increases in the elastic stage, while increases at first and then decreases in non-linear elastic loading stage. The absorbed energy of rock is very little with nearly no change when the impact pressure is lower, while reaches the maximum when the impact pressure gets the optimal value with the best effect of rock breaking.

3. Under cycle impact, the rock failure requires the impact energy exceeding the lowest rock breaking energy. The peak strain and single absorbed energy of rock are little when the impact pressure is lower (0.56 MPa), while decrease first and then increase when the impact pressure is higher (0.58–0.62MPa). Once the impact pressure reaches a high value (0.64 MPa), the impact energy exceeds and the rock is subjected to instant impact failure.
Acknowledgments
This work is supported by Youth Program of National Natural Science Foundation of China (51608521).

References
[1] Hua Jiang, Yusheng Jiang, Jinxun Zhang, et al. Research on cutterhead torque during earth pressure balance shield tunnelling in sand gravel strata of Beijing Metro[J]. China Railway Science, 2013, 34(3):59-65.
[2] Zhaohuang Zhang, Futian Li. TBM Construction Technology[M]. Beijing: China Water & Power Press, 2006.
[3] Gladwell. Contact problems in elasticity theory[M]. Beijing: Beijing Institute of Technology Press, 1991.
[4] Youyuan Liu. Discussion on the mechanism of rock breaking by disc cutter of tunnel boring machine[J]. Construction Machinery and Equipment, 1986, (6):22-25.
[5] Paul. B. Sikarskie D L. A preliminary theory of static penetration of a rigid wedge into a brittle material[J]. Transaction of the Society of Mining Engineers, AIME, New York, NY232, 1965, 372-383.
[6] Dutta P K. A theory of percusive drill bit penetration[J]. International Journal of Rock Mechanics & Mining Sciences, 1972, 9: 543-567.
[7] Haihui Lai. Mechanical Rock Fragmentation[M]. Changsha: Central South University Press, 1991.
[8] Zhaohuang Zhang. Discussion on rock breaking mechanism of disc cutter of full-face tunnel boring machine[J]. Mining & Processing Equipment, 1995(10):27-29.
[9] Qixing Wu. Mechanical analysis of rock breaking by disc cutter during shield tunnelling in mixed face ground conditions[D]. Guangzhou: Jinan University, 2011.
[10] Chu'an Tang, Xiaohu Xu. Measurement for dynamic complete curve of rock fracture[J]. Journal of Northeast University of Technology, 1990(03):230-234.
[11] Hua Jiang, Jinxun Zhang, Yi Su, et al. Study on soil conditioning experiments during earth pressure balance shield tunneling in sand gravel strata[J]. China Railway Science, 2013, 34(4):40-45.
[12] Mingzhong Gao, Ru Zhang, Qiiming Gong. The mechanism and practice of shield TBM tunnelling in sandy cobble stratum[M]. Beijing: China Architecture & Building Press, 2012.
[13] Hopkinson, B. A method of measuring the pressure produced in the detonation of high explosives or by the impact of bullets[J]. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 1914, 213(497-508):437-456.
[14] Kolsky, H. An investigation of the mechanical properties of materials at very high rates of loading[J]. Proceedings of the Physical Society. Section B, 1949, 62(11):676-700.
[15] Lianjun Guo, Yuehui Yang, Yuehan Hua. Test and analysis on distortion and damage of rock under impact loading[J]. Journal of Water Resources and Architectural Engineering, 2013, 11(06):31-34, 49.
[16] Yong Deng, Mian Chen, Yan Jin. Investigation of the dynamic characteristics and energy consumption for breaking rocks using the impact load[J]. Petroleum Drilling Techniques, 2016, 44(03):27-32.
[17] Jiefang Jin, Xibing Li, Junran Chang, et al. Stress-strain curve and stress wave characteristics of rock subjected to cyclic impact loadings[J]. Explosion and Shock Waves, 2013, 33(06):613-619.