Comparison of three testing methods of rock materials equations of state

Wen Liang¹, Rong Chen¹*, Zhengyue Nie¹, and Fangyun Lu¹
Deya Road 109, Kaifu District, Changsha, Hunan

Abstract. For rock materials, it is very important to use effective and reliable testing methods to obtain accurate Hugoniot parameters and further determine the equation of state (EOS) reflecting the intrinsic properties of materials. In this paper, taking marble as the experimental sample, three test methods of the Hugoniot EOS (i.e., symmetric, asymmetric, and reverse impacts) are proposed based on the first-class light gas gun experimental platform. The Displacement Interferometer System for Any Reflector is used to measure the speed history of the target plate and the arrival time of the shock wave. The electric probe is used to measure the speed of the flyer. Under the same launch conditions, at least three repeated experiments were conducted for each scheme. The experimental results showed that when the relative standard deviation (RSD) of the launch speed was controlled within 2%, the RSD of post-wave pressure and shock wave speed in the reverse impact method was the smallest, making it the best choice for the measurement of the Hugoniot EOS of rock materials. However, the symmetric impact can evaluate the impact flatness of the flying plate and the target plate by the time difference between the shock wave to reach different positions on the same plane of the target.

1. Introduction

The Hugoniot equation of state (EOS) of the rock reveals the internal stress wave propagation characteristics and the relationship among several physical parameters, such as pressure, density, and temperature, reflecting the internal characteristics of the rock. It is commonly used in various fields, such as seismic wave research [1], planetary impact [2], underground nuclear explosion [3], etc. Therefore, it is very necessary to find an experimental method that can accurately and efficiently measure the Hugoniot EOS of the rock.

The Hugoniot EOS of the rock is usually measured by plate impact. The flyer, driven by the detonation products of explosives or high-pressure gas [4-5], collides with the target plate, and particle speed, shock wave speed, pressure, and other physical parameters of the flyer or target are measured by electromagnetic meters, Displacement Interferometer System for Any Reflector (DISAR), manganin sensors, and others. Then, according to the basic relation of the shock wave, the Hugoniot parameters are obtained for the testing material. The test scheme can be divided into conventional impact [6,7] and reverse impact [8-10] according to the different positions of the testing rock. The sample is fixed on the target plate, and the flyer can be made of the same material (symmetrical collision) or other materials with known Hugoniot EOS (asymmetrical collision).

Based on the first-class light gas gun experimental platform, using marble as the experimental material, three experimental methods for measuring the rock Hugoniot EOS are introduced in detail,
namely, symmetrical collision, asymmetrical collision, and reverse collision. Each experimental method is repeated three times under the same launch pressure, and the consistency of the three test methods is judged by comparing the RSD of the shock wave speed and the post-wave pressure.

2. Experiments

2.1. Experimental device
A 57 mm caliber first-class light gas gun is used in the experiment. The flyer is attached to a hollow-shell aluminum holder and driven by high-pressure gas. Under the same launch pressure, the initial velocities of the flyers are approximately the same, and the RSD does not exceed 2%. A self-made electric probe is installed near the target to detect the initial speed of the flyer and trigger the oscilloscope. The DISAR is used to detect particle velocities in different planes on the target. The laser has a wavelength of 1550 nm and a power of 380 W. The rock sample used in the experiment is marble, composed of 99% calcite and a small amount of quartz, with a diameter of 50 mm and a thickness of 10 mm. The main particle size of the rock sample is 0.5~2 mm. In asymmetric collisions and reverse collisions, oxygen-free copper with a 50 mm diameter and 10 mm thickness is used to assist the measurement.

2.2. Three experimental methods
When the target is impacted with the flyer, shock waves propagating in opposite directions will be generated in the flyer and the target, respectively. We assume that the shock wave speed is \(D\), the particle speed and pressure in the front of the shock wave are \(u_0\) and \(p_0\), respectively, and the particle speed and pressure behind the shock wave are \(u\) and \(p\), respectively. From the law of conservation of momentum, the basic relationship of shock waves can be obtained as:

\[
p - p_0 = p_0(D - u_0)(u - u_0)
\]  

(1)

Before the shock wave arrives, the pressure \(p_0\) is usually equal to 1 atm, which is much smaller than the pressure behind the wave, hence it can be ignored. When \(u_0 = 1\),

\[
p = p_0 Du
\]  

(2)

Various experimental results have proved that the Hugoniot EOS of all condensed media, including solids under low pressure (less than 1 GPa) can be expressed by the linear relationship between shock wave speed \(D\) and the post-wave particle speed \(u\).

\[
D = c_0 + \lambda u
\]  

(3)

where \(c_0\) and \(\lambda\) are the Hugoniot parameters. Three methods for measuring the Hugoniot parameters of rock materials are proposed as follows:

2.2.1. Symmetric impact. As shown in Figure 1, the flyer is made of marble, and the target is composed of two pieces of marble of the same size spliced together. The photograph of the targets is shown in Figure 2. Four 3 mm through-holes are punched on target 2 for inserting optical probes to monitor the time when the shock wave reaches the interface of the two targets. To avoid the influence of the lateral sparse wave, the distance between the through-holes and the boundary of the target should be greater than 10 mm. An aluminum foil with a diameter of 2.5 mm and a thickness of 0.02 mm is pasted on target 1 at the position corresponding to the through-hole of target 2 for reflecting laser. An aluminum foil with a diameter of 10 mm and a thickness of 0.02 mm is pasted on the free surface of target 2, and a pedestal for fixing the optical probe is pasted on the aluminum foil. The optical probe is used to measure the particle speed history at the interface of the two-layer target at free surface of target 2. The shock wave speed can be calculated by dividing the thickness of the target 2 by the time difference of the take-off point of the particle speed curve at different interfaces. According to the law of speed multiplication on the free surface, the particle speed behind the shock wave is equal to half of the particle speed at the free surface. The Hugoniot parameters could be obtained by linear fitting of the
shock wave speed and particle speed behind the shock wave under different impact velocities. In addition, this method could also evaluate the flatness of the impact between the flyer and the target by the time shock wave reaches different positions of the contact interface between targets 1 and 2.

2.2.2 Asymmetric impact. The fly piece and target 1 are made of oxygen-free copper, and target 2 consists of marble. The free surface speed \( u_{f1} \) of the marble is measured by an optical probe, and the flyer speed \( w_1 \) is measured by an electric probe. The principle diagram of obtaining the post-wave pressure and shock wave speed in marble through the impedance matching method is shown in Figure 3. \( H_1 \) represents the impact compression line of the copper target, \( H_2 \) represents the impact compression line of the marble, and point A represents the state of the copper target after collision with the copper target. Since the flyer is made of the same material as target 1, the speed \( u_1 \) and the post-wave pressure \( p_1 \) corresponding to point A can be expressed by the following formula:

\[
u_1 = 1/2w_1, \quad p_1 = \rho_{Cu}(c_{Cu} + \lambda_{Cu}u_1)u_1 \quad (4)\]

where \( \rho_{Cu} \) is the initial density of Cu with a value of 3.94 g/cm\(^3\), and \( c_{Cu} \) and \( \lambda_{Cu} \) are the Hugoniot parameters of oxygen-free copper with values of 8.93 \( km/s \) and 1.49, respectively. When the shock wave in the copper target propagates to the interface between copper and marble, since the wave impedance of the marble is less than that of copper, a sparse wave will be reflected in the copper target, and the corresponding isentropic unloading line is shown by curve \( R_1 \). The intersection point B of \( R_1 \) and \( R_2 \) represents the state of marble and copper after the shock wave is reflected at the interface. To facilitate analytical calculations, shock compression line is used instead of the isentropic unloading line, that is, \( R_1 \) is obtained by mirror inversion of the \( H_1 \) curve. The equation for the \( R_1 \) curve:

\[
p = \rho_{Cu}(c_{Cu} + \lambda_{Cu}(2u - u_1))(2u - u_1). \quad (5)\]

The equation for the \( R_2 \) curve:

\[
p = \rho_{M}(c_{M} + \lambda_{M}u)u \quad (6)\]

where \( \rho_{M} \) is the initial density of the marble with \( c_M \) and \( \lambda_M \) as the Hugoniot parameters.

According to the law of multiplication of free surface speed, the post-wave particle speed in marble can be obtained by \( u_2 = 1/2u_{f1} \). The post-wave pressure \( p_2 \) at point B can be obtained by equation (5), and the shock wave speed in marble by equation (2).
2.2.3 Reverse impact. In this scheme, the flyer is marble, and the target is an oxygen-free copper. The initial speed $w_2$ of the flyer is measured by the electric probe, and the free surface speed $u_2$ of the target is measured by an optical probe. The post-wave particle speed $u_3$ in the copper target is equal to $1/2u_2$. According to equations (2) and (3), the post-wave pressure $p_3$ of the copper target is equal to $\rho C_p (c_C + \lambda C_s u_3) u_3$. It is evident from the contact interface conditions that the post-wave particle speed and post-wave pressure of marble in the laboratory coordinate system are consistent with those of copper. Taking the flyer as the reference frame, the post-wave particle speed $u_4$ of the marble is equal to $w_2 - u_3$. The shock wave speed in marble can be obtained by equation (2).

3. Results and discussion
The typical speed history curves of points A1, A2, A3, and A4 on the contact interface of target 1 and target 2 and points B1 and B2 on the free surface of target 2 are measured by DISAR as shown in Figure 4. Considering the average take-off time of the four curves A1–A4 as the time for the shock wave to reach the interface between targets 1 and 2, and the average take-off time of the two curves B1 and B2 as the time for the shock wave to reach the free surface of the target 2, the shock wave velocity $D$ of 6.196 km/s could be obtained by dividing the thickness of target 2 by the time taken by the shock wave to pass through target 2.

![Figure 3. Schematic diagram of impedance matching method.](image)

![Figure 4. The speed history curves of points A1, A2, A3, and A4 on the contact interface of targets 1 and 2 and points B1 and B2 on the free surface of target 2.](image)
In addition, the average take-off time of the four curves A1–A4 can be used to judge the impact flatness between the flyer and the target. Assuming the first take-off time as zero, the take-off times of the four curves are 0, 0.0506, 0.2048, and 0.256 μs, respectively. The time interval for the shock wave to reach from point A1 to point A4 is the longest, and the distance between points A1 and A4 is 30 mm, the angle \( \theta \) between the flyer and the target plate can be obtained by the following equation:

\[
\theta = \frac{D \cdot \text{max}(\Delta t)}{l} = \arcsin(0.256(\mu s) \times 6.196(km/s) \div 30(mm)) = 0.17^\circ
\]  

(7)

where max(\( \Delta t \)) is the maximum time interval for the shock wave to reach different positions, and \( l \) is the corresponding distance.

The post-wave particle velocity \( u \), post-wave pressure \( P \), shock wave velocity \( D \), and the RSD of each physical quantity of the three methods are shown in Table 1. In the three test methods, when the RSD of the post-wave particle velocity is controlled within 2%, the RSD of the shock wave velocity and post-wave pressure measured by reverse impact method are the smallest, making it the best method to measure the Hugoniot parameters of rock material. The RSD of the post-wave pressure in the symmetric impact is the largest, possibly caused by large particles in the marble and poor surface flatness. Large particles in the rock material will also affect the pressure measurement of the piezo-resistance sensor [10]. Therefore, when measuring the Hugoniot parameters of rock materials, materials with known Hugoniot parameters and good surface smoothness are suitable to assist the measurement.

| Method  | \( u \) (m/s) | RSD of \( u \) | \( D \) (km/s) | RSD of \( D \) | \( P \) (GPa) | RSD of \( P \) |
|---------|---------------|----------------|---------------|----------------|---------------|----------------|
| Method 1| 109.7         |                | 6.549         |                | 1.933         |                |
|         | 106.0         | 1.81%          | 6.735         | 4.22%          | 1.921         | 4.51%          |
|         | 106.8         |                | 6.196         |                | 1.780         |                |
| Method 2| 173.2         |                | 6.577         |                | 2.891         |                |
|         | 173.2         | 1.00%          | 6.794         | 2.97%          | 3.016         | 3.38%          |
|         | 170.2         |                | 6.98          |                | 3.092         |                |
| Method 3| 142.9         |                | 6.717         |                | 2.582         |                |
|         | 145.7         | 1.39%          | 6.874         | 1.32%          | 2.694         | 2.15%          |
|         | 146.8         |                | 6.721         |                | 2.654         |                |

4. Conclusion

Three methods for testing the Hugoniot EOS of the rock material are introduced, namely, symmetric impact, asymmetric impact, and reverse impact, and the consistencies of the three test methods are compared. It was found that in reverse impact method, the RSD of the post-wave particle velocity is controlled within 2%, the RSD of the post-wave pressure and shock wave velocity are the smallest, making it optimum for testing the Hugoniot parameters of the rock. Large-particle crystals inside the rock material adversely impact the experimental test results, which could be avoided by using homogeneous materials with known Hugoniot parameters.
References

[1] Boheler R High-pressure experiments and the phase diagram of lower mantle and core materials. 2000 Rev. Geophys 38 221–245.
[2] Kenkmann T, Poelchau M H, Wulf G Structural geology of impact craters. 2004 J. Struct. Geol. 38 156-182.
[3] Short N. M. Effects of shock pressures from nuclear explosion on mechanical and optical properties of granodiorite. 1966 J. Geophys. Res 71 1195–1215.
[4] Bourne N. 2013 Materials in mechanical extremes: Fundamentals and applications (Cambridge: Cambridge University Press).
[5] Field J. E., Walley S. M., Proud W. G., Goldrein H. T., Siviour C. R. Review of experimental techniques for high-rate deformation and shock studies. 2004 INT J IMPACT ENG 30 725-775.
[6] Zhang Q. B., Braithwaite C. H., Zhao J. Hugoniot equation of state of rock materials under shock compression. 2017 PHILOS T R SOC A 375 20160169.
[7] Chen Z. A., Yuan X. H., Huang X. G., et al. A shock wave experimental study on Damaping olivine and estimation of its parameters for equation of state. 2016 Chinese J. Geophys. (in Chinese) 59 152-156.
[8] Guest A. R., Braithwaite C. H., Proud W. G., and Field J. E. The shock Hugoniot properties of geological materials and relationship to static properties. 2007 AIP Conf. Proc. 955 1379-1382.
[9] Hall C.A., Chhabildas L.C., and Reinhart W.D. Shock Hugoniot and release in concrete with different aggregatesizes from 3 to 23 GPa. 1999 INT J IMPACT ENG 23 341-351.
[10] Braithwaite C. H., Proud W. G., and Field J. E. The Shock Hugoniot Properties of Quartz Feldspathic Gneiss and Amphibolite. 2006 AIP Conf. Proc. 845 1435-1438.
[11] Meyers M. A. 1994 Dynamic behavior of materials (New York: JohnWiley & Sons, Inc).