Liquid-filling auxiliary device for liquid-filled rock joints and its application

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Abstract. Filling joints are relatively common in rock mass-based geotechnical engineering. Presently, many researchers have concentrated on the analysis of filling joints with a solid or solid–liquid mixture as filling materials, while only few scholars have been investigating the filling conditions of liquid. In this study, a liquid-filling auxiliary device was developed. The primary test flow on a typical sample and its application in dynamic response to filling liquid were introduced. Granite and plexiglass were selected as test samples to emulate the structure of liquid-filled jointed rock mass, and a split Hopkinson pressure bar was employed for dynamic testing of the structure. The test results reveal that during data collection, pressure response of the filling liquid suddenly rises, experiences multiple fluctuations, and then gradually stabilizes. With an increase in the initial thickness of the filling liquid, peak value of the liquid pressure change exhibited an increasing trend. Further, dynamic response characteristics of filling liquid in liquid-filled jointed rock mass were analyzed. The outcomes provide a reference for the experimental study on the interaction mechanism between the stress wave and jointed rock mass and liquid.

1. Introduction

Due to blasting or earthquakes, dynamic loads can cause generation and propagation of stress waves that in turn affect the safety of geotechnical engineering with rock mass as the main body. Natural rock masses often contain many joints. The joints not only reduce the strength of the rock mass but also greatly impact the propagation of stress waves in the structural plane of the rock mass [1–5]. Joints are classified into open, closed, and filling joints. In the case of filling joints, the filling material can be a solid such as minerals, solid–liquid mixture such as water-containing sand and clay, or liquid such as water and oil [6–10].

Dynamic characteristics of joints and their impact on the propagation of stress waves are one of most trending research fields in rock dynamics. Many scholars have performed a series of studies and obtained interesting results with reference values. In terms of testing, the split Hopkinson pressure bar (SHPB) test is one of the main experimental methods utilized to assess the mechanical properties of materials at medium- and high-strain rates (10²–10⁴ s⁻¹) and the dynamics of materials such as rock and concrete. Various tests have been extensively conducted using this method [11–17], and related research highlights in the literature are summarized as follows.

Ju et al. [18] selected two samples with different lithologies (marble and granite) for testing and analyzed the irregularity or roughness of the joint surface configuration that clearly affected the propagation properties of stress waves and the nonlinear deformation of joints. Li et al. [19] utilized
the SHPB device made of rods, which were made from granite materials, and selected sand layers with different water contents and thicknesses as joint fillers to explore the propagation law of stress waves in the filling joints. Ma et al. [20] established a three-phase gas–liquid–solid model and then studied the impact of the thickness of the filling joint and water content in the three-phase model on the stress wave transmission coefficient. Li et al. [21] employed the fractal damage theory to process the marble sample through a three-point bending test to obtain a fractured surface to produce an artificial joint. Furthermore, the relation between the fractal dimension of the joint surface and the stress wave transmission coefficient and reflection coefficient was explored thoroughly. Liu et al. [22] defined contact area of the specimen to cross-sectional area of the incident rod as the contact area ratio. The SHPB device was utilized to test the granite sample. With the increase of the contact area, transmission coefficient that corresponded to the change in stress wave energy increased gradually. Wu et al. [23] employed granular materials as fillers to shape them in various water states, such as dry-to-full saturation, and investigated the relation between stress-wave attenuation factor and moisture content of the jointed fillers. Then, the increased water presence was highlighted. Degree of stress-wave attenuation during propagation and the impact of kaolin content, joint thickness, and other factors on stress wave transmission performance were analyzed. Chen et al. [24] cut granite and aluminum sample separately to ensure they have a different number of grooves and groove depths and then selected an improved SHPB device and aluminum SHPB device to study the contact area ratio. The stress-wave transmission coefficient was affected by the thickness of joints and other factors. Huang et al. [25] calculated the particle size of quartz sand that was propagated by stress waves of different amplitudes and divided the quartz sand deformation into three stages; initial compaction, crushing flow, and mixed crushing compaction. Li et al. [26] grooved the surface of the cylindrical granite and studied the impact of the joint coincidence coefficient on the transmission and reflection coefficients of the stress wave that propagated in the jointed rock mass. Liu et al. [27] designed a separate shear-plate device to generate shear waves, utilized hydraulic devices to apply normal stress, filled the rock layer with sand to emulate filling joints, and investigated the degree of stress-wave attenuation and joints subject to the action of shear waves.

In the cases of more common filling joints with engineering significance, many researchers have concentrated on investigating solid or solid–liquid mixtures, while only few scholars have conducted systematic research on liquid filling. One of the major goals that should be achieved urgently in the field of rock dynamics is exploring the attenuation law of stress waves in liquid-filled jointed rock masses along with revealing the dynamic response characteristics of liquids in liquid-filled jointed rock masses. Hence, related research on underground engineering, hydraulic engineering, and oil and gas reservoir resource exploration are crucial [28–32].

In this study, cylindrical granite and plexiglass are used as test samples that are combined with the self-developed liquid-filling auxiliary device to complete the emulation of the liquid-filled jointed rock mass structure, while a SHPB device is employed to apply dynamic loads. The primary test process for a typical sample and its application in dynamic response to filling liquid were introduced. The initial thickness of the filling liquid was selected as independent variables to investigate changes of the peak pressure of the filling fluid subject to the impact load of the tested sample to promote development of stress wave-jointed rock mass–liquid interaction mechanism.

2. Liquid-filling auxiliary device

The SHPB device is selected as the dynamic load application device. The impact bar affects the incident bar subject to the action of driving gas to generate stress waves. The stress wave propagates through the incident bar, sample, and transmission bar. Resistance strain gauges are arranged on the incident and the transmission bar to collect dynamic data signals during the impact process. To simulate the structure of the liquid-filled jointed rock mass, the liquid-filling auxiliary device of the liquid-filled jointed rock mass for the flanged SHPB was developed, as shown in Figure 1. The main part of the device is an integrally formed metal cavity shell. The two sides of the metal cavity shell were perforated to place the sample, and a rubber sealing ring was installed on the outside of the
sample. Two metal ball valves were symmetrically arranged on the side wall of the metal cavity to control the injection and discharge of the liquid in the cavity. To determine the dynamic change of the filling liquid at the position of the rock joint surface during the dynamic impact process, the side wall of the metal cavity was perforated to install the dynamic hydraulic sensors. It is utilized to determine the dynamic hydraulic pressure change signal. Figure 2 presents the dynamic hydraulic sensor.

Figure 1. Liquid-filling auxiliary device for liquid-filled rock joints.

Figure 2. Dynamic hydraulic sensor.

This test was conducted on granite, which has a hard texture and high strength and is beneficial to the smooth progress of the rock dynamics test. The granite core was processed with wire-cutting and automatic-surface-grinder equipment into cylindrical samples for subsequent use. The parameters of granite rock samples are listed in Table 1. To reduce the difference and unevenness of the rock material itself, the same size plexiglass material was selected for simultaneous testing. The density of the corresponding plexiglass sample was 1.18 g/cm³, the static elastic modulus was 3.15 GPa, and the dynamic elastic modulus was 4.35 GPa.

Table 1. Parameters of the rock sample.

| Parameter Type                      | Value  |
|-------------------------------------|--------|
| Height (mm)                         | 126    |
| Diameter (mm)                       | 63     |
| Density (g/cm³)                     | 2.62   |
| Static compression modulus (GPa)    | 18.9   |
| Static compression strength (MPa)   | 154    |
| Dynamic compression strength (MPa)  | 240    |

3. Main test flow
The test was divided into three steps: the installation of the samples, injection of the liquid, and impact testing.

We began with the sample installation step using a granite material sample as an example. First, a rubber seal ring was placed on the surface of the rock sample and the position of the seal was adjusted to ensure that the liquid at the joint surface had a specific initial thickness. The rock sample was subsequently placed into the cavity inside the liquid-filling auxiliary device and a flange was loaded;
the sides of the flange contained grooves that were in contact with the cavity surface. Finally, adjustments were made to the depth of the flange screw to apply pressure to the flexible rubber ring.

The next step was injecting the liquid (see Figure 3). The water injection valve A near the hydraulic pressure sensor was opened and the outlet valve B was closed. The injector was connected to a plastic conduit and the device cavity was filled with the liquid. Then, the water injection valve A was closed and the device outlet valve B was opened. The outlet valve B was immersed in a liquid-filled sink while the water injection valve A and outlet valve B were opened. The injector was used to suck the liquid from the cavity to the conduit. Given that the outlet valve B was connected to the liquid in the sink, the liquid flowed through the device, through the plastic conduit, and into the injector. When the injector was full of liquid, the suction operation was repeated 3–5 times. The purpose of the suction operation was to expel bubbles in the cavity to ensure that the liquid had filled the cavity and to reduce interference by bubbles during testing.

Figure 3. The water injection valve A and outlet valve B.

Finally, the impact test was conducted, as demonstrated in Figure 4. The liquid-filling auxiliary device was placed on the SHPB device and connected to the dynamic liquid pressure sensor. Additionally, it was fastened to the peripheral metal frame with a steel wire rope to prevent damage to the device from slips or collisions. The SHPB was then started to generate stress waves that propagated into the incident bar under the influence of the impact bar. The stress waves propagated through the incident bar, sample, and transmission bar, respectively. Data were collected and saved in a file throughout the test procedure.

Figure 4. Schematic diagram of the liquid-filling auxiliary device used in combination with SHPB.

4. Application for dynamic response to filling liquid
A sample with a 0° inclination angle was selected, and the axial separation distance was adjusted at the location of the joint surface of the sample. Therefore, the filling layer of the liquid-filled jointed rock mass had different thicknesses, the value of which varied from 1 to 5 mm. Dynamic hydraulic sensors and resistance strain gauges, arranged on the SHPB, collect data during dynamic load applications.

Figure 5 presents the typical time-history curve of the dynamic signal corresponding to the liquid with a single initial thickness. The blue and red solid lines represent different strain signals, collected by the strain gauges, on the incident and the transmission bar, respectively. The change process of the liquid pressure is indicated by the orange dotted line. During the data acquisition period, strain signal on the incident bar exhibited a smooth weakening trend. The strain signal on the transmission bar was
initially small and then slightly increased and oscillated. Further, the pressure value of the filling liquid exhibited a sudden increase, experienced many fluctuations, and then decayed and attained a stable value.

**Figure 5.** Typical time-history curve of dynamic signals.

Figures 6 demonstrates the time-history curves of the liquid dynamic responses of granite samples at various initial thicknesses of the filling liquid. Figure 7 reflects the relation between the peak pressure and the initial thickness of the liquid-filled jointed rock mass subject to impact loading. The corresponding results of granite and plexiglass materials evince an increasing trend. When the initial filling liquid thickness is the same, the peak pressure of the filling liquid corresponding to the granite is slightly larger than that of the plexiglass. For instance, when the initial thickness is 1 mm, the peak pressure of the filling liquid corresponding to the entire process of the granite is 2.66 MPa and that of the plexiglass is 2.26 MPa. When the initial thickness is 5 mm, the corresponding value for the granite and plexiglass is 5.56 MPa and 5.45 MPa, respectively [33].
Figure 6. Typical time-history curves of liquid pressure for various initial liquid thicknesses (granite).

Under dynamic impact load, owing to the interaction of the incident bar, transmission bar, and jointed rock mass structure, the specimen moves in the direction of the bar. This in turn compresses the liquid volume in the liquid-filling device and causes the liquid pressure to change. When the initial thickness of the filling liquid is large, the volume of the liquid that can be compressed is also relatively large, and the degree of change is relatively drastic, which results in a greater peak pressure of the filling liquid during the entire process. Liquid water is less compressible. However, under relatively violent impact loads, a certain degree of compression will also occur in a short time, which results in changes in liquid pressure.

![Image](image_url)

Figure 7. Liquid pressure (peak value) curves for granite and plexiglass for various initial liquid thicknesses.

5. Conclusion
In this study, a liquid-filling auxiliary device was developed for liquid-filled jointed rock samples of flanged SHPB. The main test flow for typical sample and the application in dynamic response to filling liquid were introduced. A series of characteristics of the dynamic response of liquid-filled jointed rock mass were investigated and analyzed. By adjusting the axial separation distance of the sample, different initial thickness values of the filling liquid were obtained. The results conclude that the self-made, flange-type, liquid-filling auxiliary device was useful for the emulation of the liquid-filled jointed rock mass structure and convenient for testing the evolution law and response characteristics of the liquid-filled, jointed rock mass structure subject to dynamic loads. Moreover, during the entire data monitoring process, the overall signal changes exhibited the following characteristics: the strain signal on the incident bar gradually weakened, the corresponding strain signal of the transmission bar was initially small and then slightly increased and oscillated, and the pressure value of the filling liquid suddenly experienced multiple fluctuations and then gradually stabilized. In the cases of granite and plexiglass materials, as the initial thickness of the filling liquid increased, the peak value of the liquid pressure change showed an increasing trend. When the initial filling liquid thickness was the same, the peak pressure of the filling liquid that corresponded to the granite was slightly larger than that of the plexiglass.

In future studies, dynamic load impact strength can be increased and additional devices, such as dynamic visual monitoring, can be added to explore the mechanism and change rules of the failure of the liquid-filled jointed rock mass structure, which will allow further exploration of the stress wave-joint rock mass–liquid interaction mechanism.
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