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A novel and versatile apparatus for brittle rock deformation

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ABSTRACT

This paper describes a new biaxial rock deformation apparatus within a pressure vessel, consisting of a stainless steel vessel with an internal diameter of 40 cm and six main access ports for electronics (~100 pins), pore fluids (three lines), and confining oil. The apparatus has to ability to work on large rock samples, up to 20 × 20 cm^2, with horizontal and vertical forces up to 1.5 MN. The maximum confining pressure of the vessel is 70 MPa, and fluid flow properties and permeability of large-samples can be tested using up to 8 L of fluids that can be pressurized up to 30 MPa. Sliding velocity during experiments is in the range 0.1 μm/s – 1.0 cm/s. The machine stiffness is 0.91 kN/μm and 1.3 kN/μm for the vertical and horizontal axes, respectively. Measurements on friction, velocity dependence of friction and healing properties of reference material like granite and talc replicate the values presented in the literature. Triaxial stress state tests with controlled confining and pore fluid pressure, and fluid flow through the samples have been performed successfully. The machine is extremely versatile, as it works as a uniaxial, triaxial or true-triaxial apparatus, on rock samples with dimensions ranging from several to tens of centimetres. Due to the broad number of potential operating conditions, we decided to name the machine BRAVA: Brittle Rock deformAtion Versatile Apparatus.

1. Introduction

A typical biaxial apparatus consists of vertical and horizontal load frames that are used to apply normal and shear forces on a fault rock sample. In the double-direct shear configuration [1–3], three rigid forcing blocks, one center block and two side blocks, sandwich two identical layers of the fault rock (Fig. 1). The horizontal piston applies a constant horizontal force, holding the blocks in place. The center block is then forced between the two stationary side blocks by applying either a constant sliding velocity or constant vertical force through the vertical piston.

The biaxial deformation apparatus is an important piece of equipment used to study the frictional properties of fault rocks. Different designs, each with their own strengths, have been constructed in various rock deformation laboratories around the world. One of the first biaxial apparatus used to investigate the frictional properties of rocks was built at USGS in Menlo Park, USA [1]. Subsequently, a large biaxial press was then developed in the same USGS laboratory. This press is capable of working on samples 150 cm × 150 cm × 40 cm with a precut fault surface (200 cm long) along the diagonal [4]. In this apparatus, the increased specimen size provides opportunities for improved recording resolution and greater control of experimental variables [4,5]. Another pioneer apparatus, used to investigate rock friction and its implications for earthquake mechanisms, was built at the Lamont–Doherty Earth Observatory, USA [6]. In this apparatus, the rock sample is a slab, 3 cm × 3 cm × 18 cm, with a saw cut inclined at 30° across its major faces. The assembly is loaded in a biaxial loading frame fitted with two 1 MN hydraulic pistons. A high temperature biaxial frictional testing apparatus is hosted at Kyoto University [7]. The machine can exert a force of ~200 kN on fault rock samples with dimensions of several centimeters. The sample assembly is covered by a furnace that controls temperature up to 1000 °C. At Tokyo University, a large double-shear loading apparatus was constructed [2]. In this apparatus, the length and thickness of rock samples are 100 cm and 10 cm respectively. Axial forces up to 3 MN are possible and horizontal force is exerted by three independent jacks (100 kN each), which can apply both uniform and non-uniform forces. A large biaxial apparatus is housed at the

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Institute of Geology in Beijing, China. This machine can work with fault rock samples with dimensions of 50 cm × 50 cm and thicknesses up to 30 cm [8]. A biaxial apparatus that has significantly contributed to our improved understanding on the frictional properties of fault rocks and sliding surfaces (more than 50 papers based on data collected from this machine have been published in the last decade) is found in the Rock and Sediment Mechanics Laboratory at the Pennsylvania State University (PSU). This machine can work with a maximum force of 1 MN on rock samples with dimensions up to 20 × 20 cm^2. Each load frame may be operated in displacement or load feedback servo control; displacement resolution is 0.1 μm and load resolution is 0.1 kN [9–12].

Although biaxial machines are key-apparatus to study the frictional properties of sliding surfaces and fault gouge, some important parameters for fault mechanics, such as fluid pressure and confining pressure, cannot be tested in the simple biaxial configuration. For this reason, the laboratory at PSU designed a pressure vessel that is positioned within the horizontal and vertical load frames [13,14].

In this manuscript, we present a new biaxial deformation apparatus integrated within a pressure vessel. This new apparatus is based on the system at PSU [15–17]. In order to work on larger rock samples, we designed a large vessel that would act as a combined load frame and pressure vessel (Fig. 2a). The machine is suitable for testing the petro-physical properties and mechanical/hydrologic behaviour of brittle rocks and fault rocks. At the same time, it is extremely versatile since it can work in uniaxial, triaxial (Fig. 2b) and true-triaxial (Fig. 2c) configurations, in the sense that we have the control of three independent forces, and can be used to test rock samples with dimensions ranging from several to 20 cm. Due to this versatility, we have decided to name it BRAVA: Brittle Rock deformAtion Versatile Apparatus.

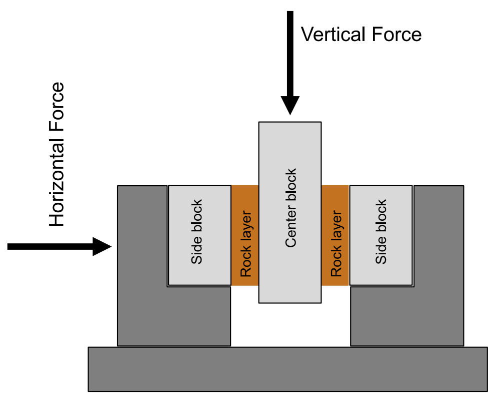

Fig. 1. Double direct shear geometry.

2. Design of the apparatus

The machine (Fig. 2a) is 2.5 m long, 2 m wide, 2.6 m high and weight 6000 kg. The apparatus consists of two orthogonal hydraulic pistons (P_V and P_H), three intensifier pistons (P_{PA}, P_{PB} and P_c), *P*, a pressure vessel (*V*), a panel with hydraulic components to drive the pistons (HC) and a box for the controlling system (CS). All parts of the apparatus are mounted on a cart. The hydraulic power supply is positioned on the roof of the laboratory, about 5 m away from the machine. The two main pistons are mounted on the vessel (Fig. 2a): one is mounted on vertical direction, P_V, for applying vertical load, the other is horizontal, P_H, for horizontal load on the experiment. The other three intensifiers are positioned on the cart (Fig. 2a): two control pore fluids P_{PA} and P_{PB} and the third one, confining oil, P_C.

In the standard triaxial configuration (Fig. 2b), the vertical load is applied by P_V, confining pressure is exerted by P_C whereas P_{PA} and P_{PB} can impose a constant pore fluid pressure or a pore pressure gradient to evaluate permeability of the rock sample. In the true-triaxial configuration (Fig. 2c), vertical and horizontal loads are applied by P_V and $P_{H,}$ respectively. P_C controls the confining pressure and P_{PA} and P_{PB} can exert a constant pore fluid pressure or a constant fluid flux perpendicular to the rock layer. In the following, we will describe the different parts of the apparatus.

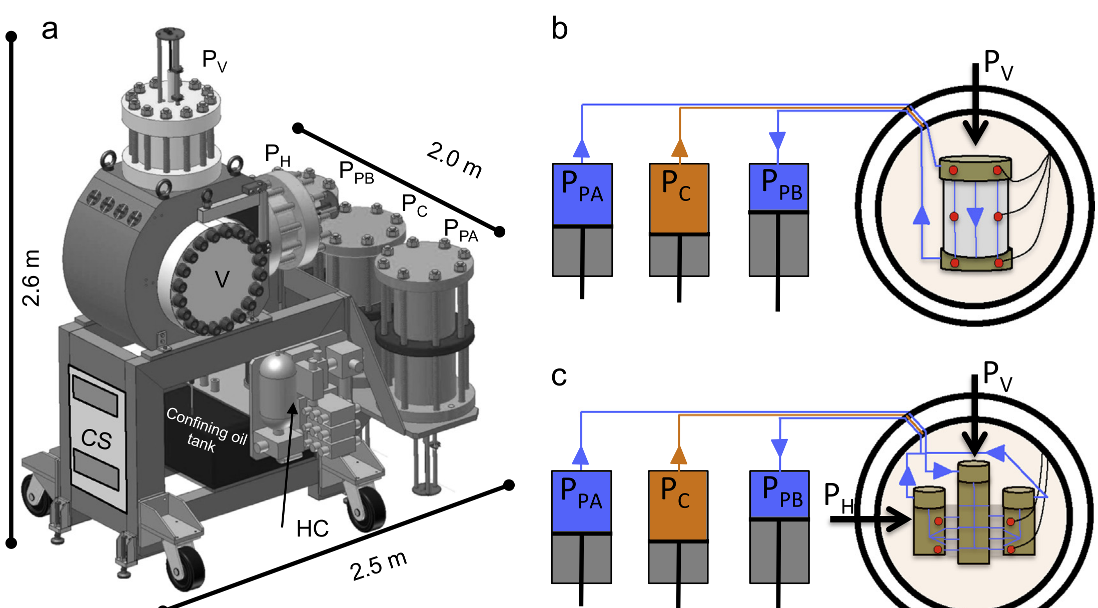

Fig. 2. (a) Schematic representation of BRAVA with the hydraulic pistons for vertical (P_V) and horizontal pressure (P_H), and the intensifiers for pore fluid pressure (P_{PA} and P_{PB}) and confining pressure (P_C), the vessel (*V*), the hydraulic control panel (HC) and the controlling system box (CS). (b) Standard triaxial configuration with pore fluid flow path. (c) True-triaxial configuration, with pore fluid flow path. In both configurations red circles are acoustic sensors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)