Static and coupled dynamic testing of granite for geological disposal of high-level waste

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Abstract. The Tianhu area of Xinjiang Province has been pre-selected for the geological disposal of high-level radioactive waste. To engineer the design of the disposal site, one must understand the static and dynamic properties of the granite in the borehole. In the present study, rock was sampled at the same depth in the same borehole, and its tensile and uniaxial-compression strengths were evaluated. Both strengths were steady and representative. The dynamic tensile and dynamic compression strengths increased with loading rate, confirming the loading rate effect on the brittle material. A coupled static-and-dynamic tension test was then carried out. Under increasing axial static stress, the dynamic tensile strength first increased and then decreased in a stable manner. The dynamic tensile strength was maximized when the static axial pre-pressure reached approximately 50% of the static-tensile strength. Meanwhile, the coupled static-and-dynamic strength increased under increasing axial static pressure, reaching approximately three times the static tension strength, and 1.5 times the dynamic tension strength. The failure model in the dynamic test was mainly tension failure, consistent with the static tension test. Therefore, the rock in this area is mechanically stable and putatively suitable for the geo-disposal of high-level waste (HLW). For a complete assessment, the rock should be tested by other methods such as seepage and in situ stress testing. After a detailed analysis of the rock in this area, the testing results and theoretical knowledge will become available for deep geo-engineering blasting and excavation, and HLW geo-disposal.

1. Introduction
High-level radioactive waste is characterized by a long half-life cycle and high toxicity. Its disposal has challenged nuclear-weapon producing countries across the globe. At present, the widely upheld feasible method is deep geological disposal. To ensure the effective isolation of the biosphere for a few thousand years or even longer, highly radioactive waste is buried in geological bodies to depths of 500–1000 m, which are stable to surface disturbances. Owing to its high stability, high strength and low permeability, granite is considered as an ideal surrounding rock for the geological disposal of high-level radioactive waste, and is also the main candidate surrounding rock for geological disposal in China [1,2].

The design, construction, support and monitoring of rock engineering are guided by the static rock parameters, such as the compressive and tensile strengths, deformation, elastic modulus, Poisson's ratio, friction coefficient, and cohesive force. However, the dynamic behavior of rock is also important for engineering [3-22]. Before the dynamic load imposed by the project excavation, rock has been in a static crustal stress state. During mining, earthquakes, and other disturbances, the high crustal stress is superimposed with the dynamic load [23-26].
The dynamic rock parameters correspond to the static rock parameters, and include the dynamic compressive and tensile strengths, the dynamic elastic modulus, and the dynamic Poisson’s ratio. In rock engineering, studying the static and dynamic loads alone cannot always meet the real requirements of an engineering project [27-38]. In particular, geological disposal for high-level radioactive waste must usually be constructed in a high two-dimensional and three-dimensional stress state. Therefore, the failure process of rock under a dynamic load can be approximately simulated by coupling the static and dynamic loads. Load coupling is more practical than considering only the action of the dynamic or static load.

During excavation, deep hard rocks in the static stress state receive a dynamic load that leads to a coupled static-and-dynamic stress state. A coupled static–dynamic loading system has been proposed elsewhere [39-42]. The failure in highly stressed hard rock has been investigated on a true triaxial servo-controlled test system and a multi-purpose static–dynamic loading test device for large-scale rock. The results showed that rock failure is dominated by the internal pre-static stress, and that external dynamic disturbance stress is an important inducer. In the seismogenic Triassic Evaporites of the Northern Apennines, the static Young’s moduli are approximately 50% lower than the dynamic moduli [43,44]. Current testing methods and analyses of rock failure appear insufficient for coupled static and dynamic loading, necessitating deeper studies [45-49]. The Tianhu area in Xinjiang Province is a preferred area for the geological disposal of high-level radioactive waste in China. Accordingly, the mechanical properties of granite in this area have been gradually researched [50]. To preliminarily understand the mechanical properties of Tianhu rock, the present study reports the results of static and dynamic loading tests on granite sampled from a borehole.

2. Testing schemes

2.1. Rock multi-functional equipment for the static test

At Sichuan University (Chengdu, Sichuan, China), the static test equipment for rock and concrete analyses is MTS815, a rock multi-functional mechanics testing system. The control equipment is a fully digitized electro-hydraulic servo control manufactured by MTS Company (US). It measures the uniaxial and three-axial compressions, atmospheric pressure, high temperatures and high pressures, pore water pressure and osmotic pressure, indirect tensile and direct stretching, three-point bending, longitudinal and transverse wave velocities, acoustic emission positioning, and testing. This rock-mechanics testing equipment operates at the highest technical level with many functions. Its parameters are given in Table 1.

| Table 1. Parameters of the MTS testing system |
|------------------------------------------------|
| Max axial pressure (kN) | Max stroke of vertical piston (mm) | Max tensile (kN) | Max confining pressure (MPa) | Overall stiffness of frame (N m/s) | Strain ratio (s⁻¹) | Frequency (Hz) |
| 4600 | 100 | 2300 | 140 | 11.0 × 10⁹ | 10⁻²−10⁻⁷ | 10⁻³−0.5 |

In the ISRM method, static axial compression tests are performed on rock cylinders of diameter 50 mm (height-to-diameter ratio = 2.0) [51]. Specimens for the static-tensile tests are Brazilian discs of approximate size Φ50 mm × H25 mm (Diameter × Height). The core is drilled to a depth of approximately 360 m, and the specimen numbers are uniformly numbered in order of 360-X, where X is [ ].

The MTS815 system can be controlled and programmed according to special test requirements. The control mode of MTS815 is easily switched among the control modes, such as axial loading control, circumferential displacement control, axial displacement control, and axial large strain control.

2.2. Rock impact equipment for the dynamic test
The dynamic rock tests were performed on the SHPB-impact equipment installed at Central South University (Changsha, Hunan, China). The incident and transmitted bars are both 75 mm in diameter. The SHPB equipment is shown in Fig.1 and its parameters are given in Table 2. All dynamic tests were performed on granite Brazilian disc specimens of approximate size Φ50 mm × H25 mm.

![Figure 1. The SHPB equipment in Central South University](image)

### Table 2. Parameters of SHPB

| Bar diameter (mm) | Length of input bar (mm) | Length of output bar (mm) | Elastic modulus (GPa) | Longitudinal wave velocity (km/s) | Poisson ratio | Pressure (MPa) | Density (kg/m³) |
|-------------------|-------------------------|--------------------------|----------------------|----------------------------------|--------------|---------------|-----------------|
| 75                | 2000                    | 2000                     | 250                  | 5400                             | 0.285        | 0–10          | 7810            |

2.3. Rock specimens

The collected rock was gray and possessed a medium-grained porphyritic texture (Fig. 2a) [52]. Its geological nature was analyzed by optical microscopy and scanning electron microscopy (SEM). The dominant minerals in the rock were identified under cross-polarized light. Figure 2b is a microscopic view of a thin section of the rock. The major constituents were quartz, alkaline feldspar, plagioclase, and biotite. On the quartz–alkali feldspar–plagioclase diagram [53], the rock fell into the monzogranite category. In addition, SEM observations confirmed a dense texture of the rock (Fig. 2c).
The average porosity of the granite at this depth is 0.682%, and the corresponding permeability coefficient is $1.83 \times 10^{-9}$ m/s [54]. These parameters confirm that the granite samples were absolutely intact and high strength.

3. Static mechanical testing

The static mechanical properties of the rock include the uniaxial tensile and compression strengths, elastic deformation modulus, and other parameters with relevance to engineering design, construction, and post monitoring. The static tensile and static uniaxial-compression parameters were obtained here.

3.1. Static-tensile testing

To compare the mechanical parameters between the static and dynamic loading tests, and to prepare a reference for determining the presupposed axial pressure of the coupled static-and-dynamic loading, engineers must determine the static-tensile strength of the rock samples.

The uniaxial axial testing was performed by an indirect test called the Brazilian disc splitting method. Prior to each test, the diameters of both ends of the specimen were measured twice in perpendicular directions, and the average of the four values was taken as the sample diameter. Similarly, the sample height was determined by averaging the heights of four circumferential points and the center point. The specimen was placed in a special fixture for loading, and the displacement loading was controlled at 0.5 mm/s. The specimen was loaded until failure while the testing data were recorded. When the tensile stress reached its peak, the indirect tensile testing was ceased immediately. Because the softening curve was not collected, it was assumed to reduce linearly from the peak stress to zero. Finally, the tensile strength was obtained using the Brazilian tensile formula.

In the static Brazilian disc splitting test, the rock usually failed along the loading direction, and the failure morphology was an approximately symmetrical semicircular disc. Both loading ends of the
rock sample remained complete, implying no obvious local stress concentration, and confirming the effectiveness and reliability of the experimental results. The average tensile strength of the rock samples was calculated as 11.75 MPa. This value was assumed as the static-tensile strength of all rock samples.

3.2. Static compression testing

The uniaxial-compression test is a static test, performed mainly to obtain the static compressive strength, static elastic modulus, and static Poisson’s ratio of the rock. Following the standard method for rock testing, the operation parameters were set and the test proceeded as follows:

1. The test sample was installed on the loading platform.
2. The longitudinal and circumferential strains of the specimens were measured by a longitudinal strain gauge with a notch distance of 50 mm and a chain-type circumferential strain gauge, respectively. The strain gauges were mounted around the specimen.
3. In axial strain-controlled loading mode, the strain rate was selected from $10^{-6}$ to $10^{-5}$ s$^{-1}$.
4. The diameter and height of the specimen, and the relevant sensor parameters, were input to the computer, which automatically calculated the loading force and stress from the loading force and area of the specimen, the strain, loading displacement, and other mechanical parameters during the testing process.
5. When the specimen bearing strength reached the maximum compressive strength and suddenly ruptured, the test reached the protection value and terminated automatically. Once the peak strength was reached, some residual strength remained, the stress slowed down, and the strain continued to develop. The stress–strain change curve was recorded at this time.

![Figure 3. Stress–strain relationship of the granite at a depth of 360 m in the borehole](image)

Figure 3 is a typical axial stress–strain curve of a specimen in the study region. The curve is divided into five stages: micro-crack compression (stage I), elastic deformation (stage II), yield (stage III), instability failure (stage IV), and rapid failure (stage V).

The uniaxial compressive strengths of the rock specimens ranged from 165 to 190 MPa. Averaging these results, the static compressive strength of the rock was determined as 175 MPa.

4. Dynamic mechanical testing

In engineering research, loading on the rock is a typical static-and-dynamic coupled loading condition. The mechanical response of the rock under coupled loading conditions is more useful in practice than the response under static or dynamic loading alone. The rock experiences not only in situ stress and other static external forces, but also dynamic forces caused by excavation disturbances. For this reason, the conventional static and dynamic tests were supplemented by a coupled static-and-dynamic test.

4.1. Dynamic compression testing

The dynamic compression impact test was conducted as follows:
1. The specimens were air-dried and the test was carried out at room temperature. Prior to testing, the stability of the testing system was verified in tests without the specimen.
2. The system was monitored to ensure tight connection between the input and output bars, and that the impact waves satisfied the basic principle of the SHPB.
The specimen was struck with the SHPB at different loading speeds.

The strain and stress of the specimen were obtained by the dynamic stress wave equations, and the testing data were checked using the dynamic force balance method.

Finally, the dynamic compressive strength of the specimen was calculated from the dynamic stress at the failure point.

The results of the dynamic compression test are given in Table 3. Under strain rates of 80 to 160 s\(^{-1}\), the dynamic compression strengths of the rock samples ranged from 138 to 208 MPa. The dynamic compressive strength increased with strain rate, verifying the dynamic rate effect of the brittle materials.

In the traditional SHPB test, the incident wave with its sharp rising edge might damage the sample upon impact. When damage occurs, the forces on each side of the specimen are unequal, and data misinterpretation is likely. To avoid this problem, the incident wave was reshaped from a rectangular pulse to a ramped wave using a C11000 copper disc. In addition, the rising slope of the incident pulse was reduced by a rubber disc placed in front of the copper shaper. This combined pulse shaping technique was employed in previous studies [55-59]. The forces on both ends of the specimen in a typical test are shown in Fig. 4.

![Figure 4. Dynamic pressure signals of a typical specimen and the dynamic balance progress of the original data (in a completely force-balanced specimen, In + Re equals Tr)](image)

The dynamic force on one side of the specimen P1 is proportional to the sum of the incident (In) and reflected (Re) stress waves, and the dynamic force on the other side P2 is proportional to the transmitted (Tr) stress wave. As shown in Fig. 4, the dynamic forces on both sides of the specimens were almost identical during the whole dynamic loading period. The inertial effects were eliminated because there was no global force difference in the specimen to induce an inertial force.

4.2. Dynamic tensile testing

The dynamic tensile test is a basic test of rock dynamic characteristics. The operation parameter settings and test processes were approximately those of the dynamic compression test, except that in the latter, the upper and lower plates of the rock sample were placed parallel to the incident bar surface and closely contacted with the transmitting bar surface, providing the required surface-to-surface contact.

In contrast, the rock sample in the dynamic tensile test was placed vertically between the incident bar and the transmitting bar. During a dynamic impact test, the rock samples must be tightened. When the sample is placed on a cushion block smaller than itself, stationary resettlement of the specimen can be ensured during the normal loading. The specimen held by the two bars is shown in Fig. 5.
4.3. One-dimensional static and dynamic coupled testing

The coupled dynamic-and-static strengths under different impact loading rates and static loads were determined in a one-dimensional static-and-dynamic coupled impact test. The coupled loading test was conducted as follows.

(1) Different levels of axial pre-static load were designed according to the static-tensile strength. The dynamic tensile strength of the rock specimen under 2–4 fractal blocks was selected as the pure-dynamic tensile strength in the coupled test.

(2) A sample smeared with Vaseline on both sides was placed between the incident and transmitting bar. After adjusting the axial pressure system, the manual pump was connected to the axial static pressure loading device, and the pre-determined axial static load was applied.

(3) Taking the pure-dynamic tensile strength as a reference, the impact pressure and position of the punch in the emission chamber were selected, and the specimen was pre-impacted under each axial compression. The dynamic test was repeated at different impact velocities under the same impact pressure at the same punch position.

(4) The signal was selected and saved by the data acquisition system, and the above steps were repeated to complete the series of tests.

(5) Impact tests under different impact loads were conducted based on a selected first type of axial pressure, and were repeated based on a second type of axial pressure.

It should be noted that the impact pressure of the punch and the impact velocity under the first axial pressure were similar to those under the other axial pressures. Thus, analyzing the impact data under different axial compression pressures and different loading conditions is appropriate.

With reference to the static and pure-dynamic tensile strengths of the rock specimens, the impact pressure was controlled at 0.3, 0.32, 0.35, 0.38, 0.40, 0.42, and 0.45 MPa. Meanwhile, the axial static load under the impact dynamic load was varied as 3.53, 5.88, 8.23, and 10.58 MPa (corresponding to 30%, 50%, 70%, and 90% of the peak static-tensile strength, respectively).

When the axial static pressure was relatively small, the elastic modulus increased as the inner part of the specimen was compressed and closed before the impact. After the impact shock, the specimen remained in the elastic state. However, under larger axial static pressures, micro cracks formed in the sample during the expansion stage, and were connected before the impact. Under this condition, the stress–strain curve bypassed the approximately elastic stage and directly entered the nonlinear stage upon impact.

Table 5 gives typical test results of the coupled static-and-dynamic tensile test. Figure 6 is the corresponding graph of dynamic tension versus loading rate, collected under a static axial tensile pressure of 3.53 MPa. Under the same static load but different dynamic loads, the coupled tensile strength of the rock specimen exceeded its static-tensile strength by 80–280%. Meanwhile, under the same loading axial pressure, the impact strength increased with loading rate.
5. Mechanical analysis of the strength properties

The deformation and failure modes of rock differ under dynamic and static loading. It is generally believed that the mechanical properties of rock change greatly under dynamic loading, and the dynamic strength is thought to far exceed the static strength. The deformation modulus also obviously increases under dynamic loading. Therefore, the mechanical strength characteristics of the rock were analyzed as described below, and the distinctions and relations among the strength parameters were systematically expounded.

5.1. Mechanical analysis of the static strength properties

From the static tensile and compression tests on the rock samples, the static tensile and compressive strengths were determined as 11.75 MPa and 175 MPa, respectively. The compressive strength was approximately 14 times higher than the tensile strength, directly confirming that the main failure mode of the quasi brittle material was tensile failure.

Meanwhile, the failure form in the tensile state implies that the rock was split into two uniform discs. The fracture surface was smooth and uniform, as typically observed in tensile failure. All of these results further confirm the failure form of the rock specimen.

5.2. Mechanical analysis of the dynamic strength properties

The tensile strength is an important parameter in engineering. The failure modes of rock are dominated by tensile failure. Combining the static and SHPB-impact tensile tests, the dynamic tensile strength was related to the loading rate under different static-tensile pressure and impact loadings. The results are discussed below.

**Figure 6.** Relationship between dynamic tension and loading rate under constant static pressure (3.53 MPa)

Figure 6 plots the relationship between dynamic tensile strength and loading rate under different impact loads. Here, the static axial tensile pressure was fixed at 3.53 MPa. As the loading rate increased from $0.55 \times 10^6$ to $0.63 \times 10^6$ MPa/s, the dynamic tensile strength was maintained at approximately 23 MPa, confirming its stability within this range of loading rates. Within a lower range of loading rates ($0.29 \times 10^6$ to $0.45 \times 10^6$ MPa/s), the dynamic tensile strength obviously increased from 17.7 to 23.18 MPa.

| No.     | $D$ (mm) | $H$ (mm) | $V_p$ (m/s) | $\rho$ (kg/m$^3$) | $\sigma_{cd}$ (MPa) | Strain rate |
|---------|----------|----------|-------------|-------------------|---------------------|-------------|
| 360-47  | 48.15    | 24.56    | 3838        | 2655              | 138.22              | 80.87       |
| 360-48  | 48.12    | 25.48    | 3803        | 2632              | 144.58              | 82.10       |
| 360-49  | 48.18    | 24.63    | 3848        | 2622              | 147.27              | 140.06      |
| 360-50  | 48.20    | 25.82    | 3972        | 2616              | 167.27              | 105.16      |
| 360-51  | 48.28    | 24.97    | 3963        | 2611              | 149.06              | 88.23       |
| 360-52  | 48.19    | 24.43    | 3940        | 2625              | 182.22              | 147.95      |
| 360-53  | 48.20    | 24.95    | 4090        | 2631              | 207.28              | 157.28      |
| 360-54  | 48.18    | 24.89    | 4880        | 2632              | 172.70              | 113.71      |
Table 4. Results of the dynamic tension test

| No.  | D (mm) | B (mm) | m (g) | ρ (kg/m³) | Vp (ms) | t (μs) | σd (MPa) | Loading rate (10⁶ MPa/s) | Strain rate |
|------|--------|--------|-------|-----------|---------|--------|----------|--------------------------|------------|
| 360-1 | 48.21  | 26.90  | 129.50 | 2638.60   | 5274.51 | 74.00  | 27.20    | 0.37                     | 4.29       |
| 360-2 | 48.25  | 26.96  | 129.50 | 2628.36   | 5502.04 | 76.00  | 32.23    | 0.42                     | 4.85       |
| 360-3 | 48.23  | 26.79  | 128.50 | 2626.80   | 5581.25 | 72.00  | 30.94    | 0.43                     | 4.96       |
| 360-4 | 48.26  | 26.81  | 129.00 | 2631.77   | 5362.00 | 74.00  | 25.23    | 0.34                     | 3.96       |
| 360-5 | 48.22  | 26.90  | 127.50 | 2596.77   | 5274.51 | 69.00  | 34.96    | 0.51                     | 5.85       |
| 360-6 | 48.31  | 26.32  | 127.00 | 2633.75   | 5371.43 | 72.00  | 32.18    | 0.45                     | 5.18       |
| 360-7 | 48.15  | 27.76  | 134.50 | 2662.20   | 5237.74 | 79.00  | 27.80    | 0.35                     | 4.07       |

Table 5. Results of the dynamic-and-static coupling tension test at constant static pressure (3.53 MPa)

| No.  | D (mm) | B (mm) | m (g) | ρ (kg/m³) | Vp (m/s) | t (μs) | σd (MPa) | Loading rate (10⁶ MPa/s) | Strain rate |
|------|--------|--------|-------|-----------|----------|--------|----------|--------------------------|------------|
| 360-8 | 48.26  | 26.86  | 128.50 | 2616.69   | 5595.83  | 46.00  | 19.22    | 0.42                     | 4.85       |
| 360-9 | 48.25  | 27.02  | 130.00 | 2632.65   | 5404.00  | 51.00  | 23.18    | 0.45                     | 5.18       |
| 360-10 | 48.32  | 26.45  | 125.50 | 2588.78   | 5397.96  | 41.00  | 23.11    | 0.56                     | 6.39       |
| 360-11 | 48.20  | 27.39  | 131.00 | 2622.50   | 4722.41  | 40.00  | 23.75    | 0.59                     | 6.72       |
| 360-12 | 48.37  | 26.46  | 125.00 | 2572.16   | 4725.00  | 36.00  | 22.59    | 0.63                     | 7.16       |
| 360-13 | 48.18  | 26.85  | 129.50 | 2646.81   | 5163.46  | 43.00  | 23.68    | 0.55                     | 6.29       |
| 360-14 | 48.29  | 26.40  | 127.00 | 2627.94   | 5387.76  | 61.00  | 17.70    | 0.29                     | 3.39       |

Figure 7. Relationship between dynamic tension and loading rate under constant static pressure (5.88 MPa)

Figure 7 relates the dynamic tensile strength to the dynamic loading rate under an axial pressure of 5.88 MPa. The dynamic tensile strength increased from 10.35 to 21.07 MPa as the loading rate ranged from 0.18 × 10⁶ to 0.59 × 10⁶ MPa/s. However, at a loading rate around 0.31 × 10⁶ MPa/s, the dynamic tensile strength remained at approximately 18.56 MPa, because the specimen had not completely cracked at the beginning of the impact load. The slightly lengthened impact time lowered the loading rate and raised the dynamic loading strength.
Importantly, under an axial pressure of 5.88 MPa, the specimen remained intact before the impact loading. In other words, the crack was not completely initiated, indicating that the specimen remained in a compact and tight state.

**Figure 8.** Relationship between dynamic tension and loading rate under constant static pressure (8.23 MPa)

Figure 8 relates the dynamic tensile strength and loading rate under an axial pressure of 8.23 MPa. As the loading rate ranged from $0.11 \times 10^6$ to $0.35 \times 10^6$ MPa/s, the dynamic strength increased from 10.67 to 17.46 MPa, but when the loading rate reached $0.3 \times 10^6$ MPa/s, the dynamic tensile strength remained at 11.44 MPa because cracks initiated in the specimen weakened the bearing capacity. Under the dynamic impact, the rock quickly reached its maximum capacity and was destroyed. Thus, the impact time under the high static pressure was relatively short and the loading rate was increased, indicating a relatively low dynamic tensile strength.

**Figure 9.** Relationship between dynamic tension and loading rate under constant static pressure (10.58 MPa)

Figure 9 plots the relationship between dynamic tensile strength and loading rate under an axial pressure of 10.58 MPa. As the loading rate ranged from $0.26 \times 10^6$ to $0.58 \times 10^6$ MPa/s, the dynamic tensile strength obviously increased from 19.35 to 23.62 MPa, but when the loading rate reached $0.39 \times 10^6$ MPa/s, the dynamic tensile strength remained at 14.37 MPa because pre-initiated micro cracks formed under this very high axial pressure. Under the dynamic impact loading, the rock quickly reached its maximum strength and was totally destroyed. The relatively short impact time indicates a low loading strength.

For an easy visual comparison, the results of Figs. 6–9 are superimposed in Fig. 10.
In conclusion, the dynamic tensile strength increased with loading rate, and the maximum dynamic tensile strength was three times higher than the static strength. This result reflects the loading rate-dependent effect on the rock materials.

5.3. Mechanical analysis of the coupled static-and-dynamic strength properties

Under a small axial static load, a specimen remained in the elastic stage, meaning that as the static load increased, the specimen showed a gradually enhanced ability to withstand coupled static-and-dynamic loads. That is, the coupled loading exerted a strengthening effect on the rock materials, and the axial static load restrained the micro-crack propagation. Especially when the crack plane was perpendicular to the axial static load direction, in the absence of axial static loading, the dynamic impact wave reflected from the surface and became a tensile wave, driving the crack expansion. However, when the axial static loading was stored, the crack gap was closed and the stress wave was transmitted with no reflection; consequently, the rock strength was largely protected from deterioration.

The failure patterns of these specimens were dominated by tensile failure mode. Under higher static-tensile pressures, the failure pattern gradually developed into compression and shear failure modes. Figure 11 plots the principal stresses at different depths and the corresponding linear fits to the data [52]. Note that the horizontal stresses gradually increased with depth. A linear regression analysis showed that within the range of stress-measurement depths, the maximum horizontal principal stress exceeded the vertical stress, indicating that the regional stress field was dominated by tectonic horizontal stress rather than by overburden load. These in situ stress results provide a reference point for selecting stress loading conditions that simulate coupled static-and-dynamic loading in the laboratory.

In situ stress measurements are more meaningful representations of compression stress than tensile stress. However, as tensile stress is also related to compression stress, the initial static-tensile stress in this paper approximates the magnitude of the in situ stresses at a certain depth.
Figure 11. Relationships between in situ stress components and depth, and their linear fits. $H$, depth below surface; $\sigma_H$ and $\sigma_h$, maximum and minimum horizontal principal stresses, respectively; $\sigma_V$, vertical stress [42]

Under large axial static pressures, the micro cracks in the rock are completely closed and internal damage begins, gradually producing new micro cracks. When a stress wave is loaded, tensile waves are reflected from the crack surface impacted by an incident wave, aggravating the expansion, nucleation and propagation of the micro cracks, and hence reducing the rock strength. Existing cracks are especially vulnerable to expansion under axial pressure. That is, when the specimen has been partially damaged before bearing the dynamic load, the deterioration will likely be accelerated when the dynamic impact is sustained.

The coupled static-and-dynamic strength increased not only with axial static pressure, but also with dynamic tensile strength. In fact, the coupled strength reached three times the static load and 1.5 times the dynamic tensile load. Our results reflect the rate-dependent effect of loading on rock materials, and also the coupled static-and-dynamic property of the rock. When the rock can withstand a large static load, its coupled static-and-dynamic tensile strength is also large, and is enhanced by the static-tensile strength. Meanwhile, the dynamic tensile strength increases first and then gradually decreases under increasing static pressure.

The dynamic impact strength generally concurred with the literature values [60]. As a function of $\%$, the dynamic impact strength trended slowly, while the amplitude variation of the coupled static-and-dynamic strength was larger, but the change laws of both parameters were consistent. The dynamic compression and tensile strengths first increased and then decreased with $\%$. However, the coupled static-and-dynamic compression strength slowly increased with axial pressure, and tended to stabilize at high pressures. Meanwhile, the coupled static-and-dynamic tensile strength continuously increased with axial pressure. This phenomenon shows that the coupled static-and-dynamic strength properly characterizes the effect of axial pressure on dynamic impact. The different impacts of the two dynamic strengths can be explained by the different mechanisms of the impact forces: one imposes a dynamic tension, while the other imposes dynamic compression. Furthermore, the range of loading rates differs between dynamic compression and dynamic tension.

6. Conclusions

The main conclusions are summarized below.
(1) Based on MTS815 and SHPB, a series of static tensile, static uniaxial compression, dynamic tension, dynamic compression, and coupled static-and-dynamic tensile tests was carried out on granite extracted from a certain depth in the Tianhu area of Xinjiang, which has been pre-selected for the geological disposal of high-level radioactive waste. The tensile and uniaxial compressive strengths were 11.75 and 175 MPa, respectively. The uniaxial-compression strength was approximately 14 times higher than the tensile strength.

(2) The dynamic tensile strength ranged from approximately 25 to 35 MPa as the loading rate ranged from $0.34 \times 10^6$ to $0.51 \times 10^6$ MPa/s. Meanwhile, the dynamic compressive strength ranged from 138 to 208 MPa as the strain rate ranged from 80 to 160 s$^{-1}$. Increasing the loading rate or strain rate increased both the dynamic tensile and the dynamic compressive strengths, demonstrating the rate-dependent effect of quasi brittle materials.

(3) In the coupled static-and-dynamic tensile loading test, the dynamic tensile strength first increased and then decreased with increasing axial static pressure. The dynamic tensile strength was maximized at approximately 50% of the static-tensile strength. Moreover, the coupled static-and-dynamic tensile strength was a rapidly increasing function of axial pressure, reaching three times the static-tensile strength and 1.5 times the dynamic tensile strength. The failure mode was dominated by tensile failure, which more-or-less characterized the static tensile and dynamic-splitting failure modes.

(4) It must be noted that the testing data are insufficient, and that the critical dynamic load should be further studied under different axial static pressures. Other tests, such as permeability and in situ stress tests, should also be undertaken, not only in one borehole, but in different kinds of boreholes at diverse depths. This study provides the corresponding experimental data and theoretical support for the blasting design of deep underground engineering and the geological disposal of high-level radioactive waste.

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