Rock borehole shear tests in dam foundation of Xiangjiaba hydropower station

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Abstract: Xiangjiaba hydropower station is one of the cascade power stations on the Jinsha River, China. Due to the complicated geological conditions of its dam foundation, evaluating the rock mass quality and determining the mechanical parameters of rock masses are very important issues. To address these issues, several groups of rock borehole shear tests (RBSTs) were conducted on the black mudstone in the dam foundation of Xiangjiaba hydropower station in the second construction phase. Forty three groups of shear strengths of black mudstone samples were obtained from RBSTs, and the shear strength parameters (c and f) were calculated using the least squares method. In addition, the limitations and merits of RBST employed in the Xiangjiaba hydropower station were discussed. Test results indicate that the shear strength parameters obtained from RBST have a good correlation with the results from sound wave test in borehole. It is believed that RBST has a good adaptability and applicability in geotechnical engineering.

Key words: rock mass; field investigation; rock borehole shear test (RBST); shear strength parameters

1 Introduction

Since the rock borehole shear test (RBST) apparatus, a new device to determine shear strength of rock masses in a 76 mm diameter borehole, was first developed by Handy et al. (1976). It has been widely used in USA, Japan, Korea, etc. (Drennon and Handy, 1972; Handy et al., 1976; Tanaka et al., 1984; Handy, 2000; Fauremezger et al., 2008). Application of RBST in China was first reported in 2009 when a rock borehole shear tester was imported by China Institute of Water Resources and Hydropower Research (IWHR). After that, RBST was considered as a promising in-situ device for determining the shear strength of rock masses (EGM Editorial Board, 2007).

For a rock project, how to reasonably determine the mechanical parameters of rock masses is one of the most important issues (Gu, 1979; Hoek and Brown, 1980). Although a number of laboratory and field test methods associated with the experience of geologists can be used to determine the mechanical parameters of rock masses, they have been only used in large-scale construction projects due to its high cost and time consumption. The RBST apparatus, applicable to soft-medium strong rocks (Fauremezger et al., 2008), can measure the shear strengths of rock masses in a rapid, simple and reliable way. The drawbacks of laboratory and field test methods are presently observed due to the small number of tests and possible disturbance on rock masses when sampled. Fortunately, the application of RBST can overcome the limitations of the laboratory and field test methods to some extent.

Because the Limeiwan fold passes through the Xiangjiaba dam site, the site-specific geological conditions are extremely complicated. Thus, it is difficult to determine the mechanical parameters of rock masses using conventional test methods. Thereby, the RBST was recommended for the shear strength determination of rock masses in the dam foundation. The detailed RBST process and results for Xiangjiaba hydropower station will be discussed below.
2 RBST method, apparatus and procedure

2.1 Test method

The general structure of RBST apparatus and the test method (Wang et al., 2011) are shown in Figs. 1 and 2, respectively. In this test, two opposite hardened steel-tungsten-carbide teeth are pressed into the rocks surrounding a borehole under normal pressure. The rocks between two hardened saw teeth will be sheared and broken by pulling the whole shear head using the pulling jack. Thus, this test is similar to the direct shear test on the rocks between teeth on plate. In RBST, the normal and shear stresses can be expressed as

\[ \sigma = \frac{P}{A} \]

\[ \tau = \frac{T}{(2A)} \]

where \( \sigma \) is the normal stress, \( P \) is the pressure on the shear plate, \( A \) is the area of shear plate, \( \tau \) is the shear stress, and \( T \) is the pulling force acting on the shear head (Fairemezger et al., 2008).

2.2 Test apparatus

The test apparatus consists of shear head, pumps of normal pressure and pulling strength, pulling jack, leveling plate, special pier, acme threaded rod, oil lines, etc.

Shear head is the key element of RBST apparatus. There are two opposite shear plates on shear head, and on each plate there are two hardened steel-tungsten-carbide teeth. The shear plates are mounted on the ends of a double-acting hydraulic cylinder capable of applying a maximum force up to approximately 50 kN, which are rated at 35 kPa. The size of shear plate is 2.5 cm × 2.0 cm, and the length along the borehole axis is 2.5 cm. Two parallel saw teeth on the plates cross the borehole axis with the distance of 2.2 cm. The size of rock between two saw teeth on the shear plate is basically 2.5 cm × 2.0 cm.

The pulling jack, installed at the top of rock borehole, applies the shear stress on the shear plates through pulling the acme threaded rod (Fig. 1(b)).

The pressure control device includes a manual hydraulic pump, two hydraulic pressure gauges and the selector valves of normal and shear stresses (Figs. 1(a) and 3).
With several groups of RBST data, the shear strength parameters of rock masses, including the internal friction coefficient \( f \) and cohesion \( c \), can be calculated using the least squares method:

\[
f = \frac{\sum \sigma_i \tau_i \sum \sigma_i - \sum \tau_i \sum \sigma^2_i}{(\sum \sigma_i)^2 - n \sum \sigma^2_i} \quad (2)
\]

\[
c = \frac{\sum \sigma_i \sum \tau_i - n \sum \sigma \tau_i}{(\sum \sigma_i)^2 - n \sum \sigma^2_i} \quad (3)
\]

where \( \sigma_i \) and \( \tau_i \) are the normal and shear stresses of the \( i \)-th rock sample, respectively; and \( n \) is the number of rock samples.

In a rock borehole, various RBSTs can be conducted at different depths and the shear strength parameters of rocks in this area can be determined easily from different boreholes.

### 2.3 Test procedure

The main RBST procedure is described as follows:

1. Equipment installation. According to the requirements of the equipment connection, all parts of RBST equipment should be installed precisely and no oil leakage should occur.

2. Normal pressure adjustment. Put the shear head in a borehole at a certain depth, and fix the acme threaded rod with a special pier on the pulling jack which is located on the leveling plate. The rod should be kept at the center of the borehole. Then, close the shear pressure valve and open the normal pressure valve, apply the seating pressure to make the teeth on the shear plate press into the rock mass, and keep 5 minutes for seating.

3. Application of normal and shear stresses. Apply the normal pressure to a certain level, and keep several minutes until the normal stress reaches a stable value. Then, close the normal pressure valve, open the shear pressure valve to apply the shear stress, and read the shear stress value from the gauge when it reaches the maximum value.

4. Preparation of next test. After the test, release the shear and normal stresses, remove the shear plates and pull the shear head out of borehole. Record the failure characters of rocks and then clean the shear plates ready for the next test.

For the RBST in this study, the method of normal and shear stresses applied refers to the rock shear test in the Chinese specifications for rock tests in water conservancy and hydroelectric engineering. In the RBST, because the strain under a certain stress cannot be obtained, the next test stress will be applied when this stress value is stable.

### 3 Application of RBST

#### 3.1 Description of Xiangjiaba hydropower station

Xiangjiaba hydropower station, with an installed capacity of 6 400 MW (8 generating units in total, each of 800 MW), is the last hydropower station in the hydropower cascade development project along the Jinsha River. It is the third largest hydropower station under construction in China at present. The project is mainly composed of concrete gravity dam, underground plant in the right bank, plant behind dam in the left bank, navigation structure and irrigation water intake. The length of the gravity dam is 897 m and the maximum dam height is 161 m.

The gravity dam is constructed on the foundation of the Triassic system, including the top Triassic Xujiahe group (T\(^3\)j\(^2\)) and the middle Triassic Leikoupo group. The dam foundation is mainly of fluvial and lacustrine facies sedimentary rocks, such as sandstone and mudstone. The lithologic character of foundation rocks changes significantly and the bedding structure is very complex. The Limeiwan fold in a knee shape passes through the dam area from northwest to southeast. The length of Limeiwan fold in the dam area is about 2 km (HZEC, 2009). In this area, the rock mass is intensively fractured and weak interlayers are well developed due to the Limeiwan fold. The stability against deep sliding for the concrete gravity dam of Xiangjiaba hydropower station is a very important issue.

#### 3.2 Geological settings of test site

In this study, the RBSTs were conducted at the bottom slab of stilling basin in water release dam section of Xiangjiaba hydropower station, as shown in Fig. 4. The rocks at the bottom slab of stilling basin are black mudstone of the top Triassic Xujiahe group (T\(^3\)j\(^2\)). In this area, the rocks are cut by weak interlayers and the rock joints are intensively developed. According to the Chinese Code for Engineering Classification of Rock Masses (SL264—2001), the rock masses in this area fall into classes III—IV.

#### 3.3 Field test

In the test site, 43 groups of RBSTs were performed. The borehole diameter is about 80 mm and the depth is about 4 m. The rock masses at the bottom slab of
stilling basin are shown in Fig. 5. The depth of rock borehole is less than 5 m due to the blockage of rock fragments in the borehole. Rock borehole was drilled using the compressed air drilling method, which can effectively penetrate the rocks surrounding the borehole. However, it is noted that, at the bottom of the borehole, the borehole wall may collapse and bury test equipment when considering the RBST. Thus, the RBST is suggested to be performed at the top and middle of the borehole. The rock borehole for the RBST is shown in Fig. 6.

After the RBST, the rock fragment on the shear plates and the failure mode of the rocks surrounding the borehole are shown in Figs. 7 and 8, respectively.

4 RBST results and analysis

4.1 Analysis of RBST results

From the RBSTs conducted in the dam foundation of Xiangjiaba hydropower station, 43 groups of shear strengths of black mudstone samples were obtained. The scatter diagram of 43 groups of RBST data obtained from rock boreholes RBX-1–12 is shown in Fig. 9. From the RBST data, the rock shear strength parameters can be calculated according to Eqs. (2) and (3). The internal friction coefficient $f$ and cohesion $c$ of black mudstone of 43 groups were obtained using the
least squares method. These shear strength parameters of mudstone are listed in Table 1. The average values of internal friction coefficient and cohesion in Table 1 are 0.47 and 0.8 MPa, respectively.

Table 1 Shear strength parameters of black mudstone obtained from the RBST data.

<table>
<thead>
<tr>
<th>Test group</th>
<th>f</th>
<th>c (MPa)</th>
<th>Test group</th>
<th>f</th>
<th>c (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RBX-1</td>
<td>0.43</td>
<td>0.06</td>
<td>RBX-7-3</td>
<td>0.54</td>
<td>1.08</td>
</tr>
<tr>
<td>RBX-2-1</td>
<td>0.28</td>
<td>0.65</td>
<td>RBX-8-1</td>
<td>0.46</td>
<td>0.67</td>
</tr>
<tr>
<td>RBX-2-2</td>
<td>0.33</td>
<td>2.33</td>
<td>RBX-8-2</td>
<td>0.51</td>
<td>0.45</td>
</tr>
<tr>
<td>RBX-2-3</td>
<td>0.37</td>
<td>1.25</td>
<td>RBX-8-3</td>
<td>0.55</td>
<td>0.48</td>
</tr>
<tr>
<td>RBX-2-4</td>
<td>0.37</td>
<td>0.22</td>
<td>RBX-8-4</td>
<td>0.46</td>
<td>0.37</td>
</tr>
<tr>
<td>RBX-2-5</td>
<td>0.42</td>
<td>0.13</td>
<td>RBX-8-5</td>
<td>0.54</td>
<td>0.18</td>
</tr>
<tr>
<td>RBX-2-6</td>
<td>0.58</td>
<td>0.32</td>
<td>RBX-8-6</td>
<td>0.45</td>
<td>0.94</td>
</tr>
<tr>
<td>RBX-2-7</td>
<td>0.51</td>
<td>0.14</td>
<td>RBX-8-7</td>
<td>0.36</td>
<td>1.41</td>
</tr>
<tr>
<td>RBX-2-8</td>
<td>0.53</td>
<td>1.16</td>
<td>RBX-10-1</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>RBX-2-9</td>
<td>0.53</td>
<td>0.07</td>
<td>RBX-11-1</td>
<td>0.36</td>
<td>0.88</td>
</tr>
<tr>
<td>RBX-3-1</td>
<td>0.35</td>
<td>0.81</td>
<td>RBX-11-2</td>
<td>0.39</td>
<td>0.71</td>
</tr>
<tr>
<td>RBX-4-1</td>
<td>0.47</td>
<td>1.2</td>
<td>RBX-11-3</td>
<td>0.41</td>
<td>0.39</td>
</tr>
<tr>
<td>RBX-4-2</td>
<td>0.44</td>
<td>0.2</td>
<td>RBX-11-4</td>
<td>0.43</td>
<td>0.55</td>
</tr>
<tr>
<td>RBX-4-3</td>
<td>0.44</td>
<td>0.19</td>
<td>RBX-11-5</td>
<td>0.34</td>
<td>2.29</td>
</tr>
<tr>
<td>RBX-5-1</td>
<td>0.55</td>
<td>0.62</td>
<td>RBX-12-1</td>
<td>0.43</td>
<td>1.19</td>
</tr>
<tr>
<td>RBX-5-2</td>
<td>0.42</td>
<td>0.85</td>
<td>RBX-12-2</td>
<td>0.45</td>
<td>1.24</td>
</tr>
<tr>
<td>RBX-5-3</td>
<td>0.45</td>
<td>1.78</td>
<td>RBX-12-3</td>
<td>0.46</td>
<td>0.27</td>
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<td>RBX-6-1</td>
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<td>0.98</td>
<td>RBX-12-4</td>
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<td>1.25</td>
</tr>
<tr>
<td>RBX-6-2</td>
<td>0.40</td>
<td>2.19</td>
<td>RBX-12-5</td>
<td>0.58</td>
<td>0.35</td>
</tr>
<tr>
<td>RBX-6-3</td>
<td>0.58</td>
<td>0.82</td>
<td>RBX-12-6</td>
<td>0.53</td>
<td>0.43</td>
</tr>
<tr>
<td>RBX-7-1</td>
<td>0.85</td>
<td>0.07</td>
<td>RBX-12-7</td>
<td>0.65</td>
<td>1.38</td>
</tr>
<tr>
<td>RBX-7-2</td>
<td>0.50</td>
<td>1.40</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: For symbols such as “RBX-2-1”, “2” is the rock borehole number, “1” is the test number in rock borehole “RBX-2”.

The histograms of shear strength parameters of black mudstone in the dam foundation of Xiangjiaba hydropower station are shown in Fig. 10. It can be seen that the internal friction coefficients approximately obey normal distribution, while the cohesion values obey lognormal distribution.

In Xiangjiaba hydropower station, the advantages of RBST compared with conventional in-situ normal shear test can be observed, which are of simplicity, high efficiency and good application. Thus, RBST can be utilized in exploration drilling. In addition, the shear strength parameters of rocks in different spatial orientations can also be obtained from the RBST in the rock boreholes. On the other hand, the RBST also has its limitations, for example, small shear area and shallow shear depth because of small steel teeth (1 mm) on shear plate.

In this paper, the results of triaxial compression test or direct shear test on foundation rocks are not collected, but the shear strength parameters obtained from RBST are compared with those recommended by geological engineers. According to the recommended parameters, the internal friction coefficients of rock mass of class IV are 0.55–0.75, and the cohesion values are 0.3–0.6 MPa. The shear strength parameters of rock mass obtained from the conventional test are a
little higher than the recommended ones.

4.2 Comparative analysis of RBST and sound wave test results

At Xiangjiaba hydropower station, RBST and sound wave test were conducted in the rock boreholes RBX-2 and RBX-6 in the dam foundation. The shear strength parameters \( f \) and \( c \) obtained from RBST and the acoustic velocity \( V_p \) obtained from sound wave test at the same depth of the boreholes RBX-2 and RBX-6 are listed in Table 2.

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Depth (m)</th>
<th>Shear strength parameters</th>
<th>( V_p ) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( f )</td>
<td>( c ) (MPa)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.9</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.4</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.6</td>
<td>0.53</td>
</tr>
<tr>
<td>RBX-2</td>
<td></td>
<td>2.8</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.4</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.8</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.5</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.9</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>RBX-6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For the rock masses in shallow depths of borehole RBX-2 were seriously damaged, the internal friction coefficients of rock mass obtained at depths of 1.5 and 1.9 m are smaller. Therefore, these two groups of test data are not considered.

In the correlation analysis of internal friction coefficient and acoustic velocity, the correlation coefficient \( f \) and \( V_p \) is 0.89, which can be drawn from Fig. 11. However, the correlation coefficient \( c \) and \( V_p \) is not calculated because of the discreteness of cohesion.

From the above correlation analysis, the relation of internal friction coefficient and acoustic velocity, obtained from the RBST in the rock boreholes RBX-2 and RBX-6, can be expressed as

\[
f = 2.623 \left( \frac{V_p}{10^4} \right) - 0.322
\]

At present, the relevant test data for shear strength parameters are scarce. From those limited data, it can be seen that the shear strength parameters of rock mass have a good correlation with the acoustic velocity. But further study on drillability and acoustic velocity is needed.

5 Conclusions

At Xiangjiaba hydropower station, the RBSTs were conducted on black mudstone in the dam foundation. Based on the test results, some conclusions can be drawn as follows:

(1) The shear strength parameters of rock mass were calculated from 43 groups of RBST data, and the average values of \( f \) and \( c \) are 0.47 and 0.8 MPa, respectively.

(2) The relationship between the internal friction coefficient and acoustic velocity was obtained using the least squares method. There is a clear linear correlation between \( f \) and \( V_p \), with a correlation coefficient of 0.89.

(3) From the RBST, the shear strength parameters are smaller than those obtained from the conventional tests. According to the experiences of USA and Japan, the internal friction coefficient \( f \) of rocks is slightly less than that obtained from the conventional tests when the internal friction angle \( \phi \) is smaller than 40°. But the cohesion \( c \) of rocks is generally 25%–50%, less than that obtained from the conventional tests.

(4) Compared with the in-situ conventional shear test, the advantages of RBST are of simplicity, high efficiency and good correlation.

This paper tries to present a method to obtain the shear strengths of rocks in large geotechnical projects. However, for the drawbacks of RBST, further study is necessary to support the basis of RBST application to geotechnical engineering.

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References


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