Investigation of meso-failure behaviors of Jinping marble using SEM with bending loading system

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\section*{Abstract}
In this study, the meso-failure mechanism and fracture surface of Jinping marble were investigated by means of scanning electron microscope (SEM) with bending loading system and laser-scanner equipment. The Yantang and Baishan marbles specimens from Jinping II hydropower station were used. Test results show that the fracture toughness and mechanical behaviors of Yantang marble were basically higher than those of Baishan marble. This is mainly due to the fact that Baishan marble contains a large percentage of dolomite and minor mica. Crack propagation path and fracture morphology indicated that the direction of tensile stress has a significant effect on the mechanical behaviors and fracture toughness of Baishan marble. For Yantang and Baishan marbles, a large number of microcracks occurred when the direction of tensile stress was perpendicular to the bedding plane. Conversely, few microcracks occurred when the direction of tensile stress was parallel to the bedding plane. The presence of a large number of microcracks at the main crack tip decreased the global fracture toughness of marble. The results of three-point bending tests showed that the average bearing capacity of intact marble is 3.4 times the notched marble, but the ductility property of the defective marble after peak load is better than that of the intact marble. Hence, large deformation may be generated before failure of intact marbles at Jinping II hydropower station. The fractal dimension of fracture surface was also calculated by the cube covering method. Observational result showed that the largest fractal dimension of Yantang marble is captured when the direction of tensile stress is parallel to the bedding plane. However, the fractal dimension of fracture surface of Yantang and Baishan marbles with tensile stress vertical to the bedding plane is relatively small. The fractal dimension can also be used to characterize the roughness of fracture surface of rock materials.

\section{1. Introduction}
Jinping II hydropower station is located on the Jinping Bay of Yalong River in the junction of three cities including Muli, Yanyuan and Mianning. There are four diversion tunnels in Jinping II hydropower station with an average length of about 16.67 km and the diameter of lining tunnel of about 11.8 m. Also, there are two parallel auxiliary traffic tunnels (tunnels A and B), about 60 m away from the diversion tunnel connecting Jinping I and II stations (CHIDI, 2003; HEC, 2005). In terms of site-specific geological conditions, many geological hazards, such as high geostress, water inrush, rockburst and unstable surrounding rocks, are frequently reported in the construction process of the traffic tunnels, which not only delay construction schedule, but also threaten the lives of workers (Wu et al., 2005; Zhang and Fu, 2008).

Since the earlier 1950s, researchers have been focusing on the deformation and failure mechanisms of rocks. Using high rigid testing machine and true triaxial test, more physico-mechanical properties of rocks have been understood (Paterson and Wong, 2005; Mogi, 2006; Jaeger et al., 2007). In the earlier 1970s, many studies were conducted on the mechanical properties of rocks under unloading stress paths (Swanson and Brown, 1971; Crouch, 1972). In the last three decades, studies on deep underground rocks have been developed increasingly with the major projects in high geostress regions, such as the Three Gorges project and Jinping hydropower station (Li and Wang, 1993; Wu, 1997; Zhou, 2000; You, 2002; Pei et al., 2009). However, for Jinping marbles, the results of conventional triaxial tests vary widely. Thus, the deformation and failure mechanisms and strength of rocks under unloading stress paths still remain unclear, which are challenging issues in deep underground...
engineering in China. In addition, Ha et al. (1998) and Li (1999) have
developed the theory of unloading rock mechanics concerning the
deformation and failure of rocks.

For deep rocks in Jinping hydropower station, Wang et al. (2008)
conducted 4 tests on marble specimen in the diversion tunnels of
Jinping II hydropower station under different stress paths, including
uniaxial loading and unloading, triaxial compression, pre-peak and
post-peak unloading confining pressure under high stress condi-
tions. Wu et al. (2010) showed slacking failure of marble at Jinping II
hydropower station with true triaxial blasting experiments on
coarse marble and aplite marble. Yan and Xia (2008) carried out
rheological tests on Jinping marble under multilevel unloading
confining pressures, and proposed that unloading confining pres-
sure affects the instantaneous deformation and the rheological
deformation of rocks. Huang and Huang (2010) analyzed the frac-
ture surface of specimens under triaxial unloading and scanning
electron microscope (SEM), and presented the regulations of
def ormation, failure and strength of marble at Jinping I hydropower
station under different unloading rates in high stress environments.

However, most of the above-mentioned studies focused on
macro-failure of Jinping marble and few studies are on meso-scale.
The scale of meso-failure is between those of macro- and micro-
failure. In this paper, rock failure at meso-scale was discussed,
namely at about millimeter and centimeter scales. As is known, the
failure of rock is a multi-scale mechanical process, which is very
complex and irreversible. If the information of crack initiation,
propagation and fracturing by means of in-situ observation can be
obtained, it is helpful for understanding rockburst occurring in
deep rocks of Jinping project. In this study, the meso-failure
mechanisms of marble with preset flaws and intact marble were
investigated. With the help of SEM, a series of three-point bending
tests on Yantang and Baishan marbles was also conducted.

2. Rock specimens and experimental procedure

The rock specimens were sampled from Jinping traffic tunnels A
(stake No. AK12 + 621 at Yantang) and B (stake No. BK12 + 28.7 at
Baishan), at the depth of 2010 m from surface. The two parallel tunnels
have a center-to-center distance of about 35 m, and cross-sectional
area of 5.5 m × 5.7 m (width × height) and 6.0 m × 6.3 m, respec-
tively. The depth of the tunnels is basically 1500–2000 m, accounting
for about 73% of total length. The maximum overburden depth is
about 2375 m. The rocks in the area where the tunnel passed through
consisted of marble, limestone, sandstone and other hard rocks.
Geostress of the project increases with depth, and the major principal
stress is 42.11 MPa. Slight or moderate rockburst occurred in the
tunnels PD1 and PD2 at Dashuigou when the excavation depth was up to
2000 m. Rockburst occurred occasionally at the auxiliary tunnel.
With increasing excavation depth, more serious rockburst accidents
may occur. Yantang marble in tunnel A is mainly laminar containing
54.7% calcite and 45.3% dolomite associated with marked bedding
features. Baishan marble in tunnel B contains 91% dolomite, 8.6%
calcite and only 0.4% mica. Since Baishan marble is relatively homo-
geous, it is regarded as an isotropic material.

The bending loading system is used in this study. The size of
three-point bending marble specimen was 10 mm × 5 mm × 20 mm,
as shown in Fig. 1. The experiments were conducted using the SEM
with loading system in the State Key Laboratory of Coal Resources
and Safe Mining, China University of Mining and Technology (CUMT)
(Zuo et al., 2007, 2009, 2010). Using the SEM with loading system,
crack propagation path can be continuously recorded to reveal the
meso-failure mechanism of Jinping marble. In the test, displacement
loading mode was adopted, which was set to be 10−4 mm/s.

According to the site-specific conditions, intact and layered
rocks were tested respectively to evaluate the stability of the
auxiliary traffic tunnel. According to standard three-point bending
test and mechanical behaviors of Jinping marble, the specimens
were divided into three groups, i.e., two Yantang groups (group A1
and A2) and one Baishan group (group B). The two Yantang groups
consist of group A1 with bedding plane parallel to tensile stress
direction and group A2 with bedding plane perpendicular to tensile
stress direction. Fig. 2 shows test specimens prepared for testing.

3. Tests on the meso-failure of Jinping marbles

3.1. Meso-failure characteristics of intact Jinping marble

In order to obtain meso-failure characteristics of intact Jinping
marble, the three-point bending tests were conducted on marble
specimens of Yantang and Baishan groups. Fig. 3 shows the rela-
tions between the bending stress and deflection of specimens of
the three groups. In Fig. 3a and b, it is observed that brittle frac-
turing at failure occurs in the two groups of Yantang marbles. The
deformation of all the specimens is linearly distributed with
applied load before peak, and almost no plastic deformation occurs.
Brittle failure suddenly occurs in rock specimens when the peak
load is reached. Since the direction of tensile stress induced by
bending is perpendicular to the bedding plane, Jinping marble
specimens of group A2 are more easily to fracture than those of
group A1. Experimental results show that the peak load of speci-
mens of group A1 is 1.7 times that of group A2. As shown in Fig. 3c,
ductile failure of Jinping marbles of Baishan formation is observed
when the peak load is reached, and no disintegration is observed. It
can also be noted that the residual strengths exist after the peak
load. The peak load of Baishan marble is basically lower than the
strength of Yantang marble (group A2), about 10%–30%.

According to the principle of bending theory, the deflection δ
is assumed to be linear with the imposed load P:

\[
\delta = \frac{Pl^3}{48EI}
\]  

where E is the elastic modulus of rock specimen, I is the effective
span (20 mm), and l is the area moment of inertia of the cross-
section.
Differentiating $\delta$ in Eq. (1), we have

$$E = \frac{\int^3_0 dP}{48I} \frac{d\delta}{d\phi}$$

(2)

For the linear section of the load-deflection curve, we can get $E$ as follows:

$$E = \frac{K^2}{48I}$$

(3)

where $K$ is the slope of the straight line segment.

Because the elastic stage of the curve represents linear feature, it can be expressed as

$$P = K\delta + t_0$$

(4)

where $t_0$ is the initial load.

According to the fitting data of three-point bending test using the least square method, the values of $E$ of Jinping marble were obtained. Table 1 shows the maximum bending stress and values of $E$. It is indicated that the bending stress and $E$ of Yantang marble of group A1 are the highest, while those of the Baishan marble is the lowest.

To evaluate the fracture energy of Jinping marble, the following formula is used:

$$W = \int_0^{\sigma_F} \sigma d\epsilon$$

(5)

where $W$ is the fracture energy, $\sigma$ is the stress, $\epsilon$ is the strain, and $\sigma_F$ is the peak load when the marble fractures. Table 1 indicates that the fracture energy of marble of group A2 is higher than that of Baishan marble, but lower than that of group A1. This means that risk of rockburst in Yantang marble is more severe potentially.

3.2. Fracture characteristics of marble specimens with pre-existing notch

We analyzed the failure behaviors of intact Jinping marble as mentioned above. However, there are various flaws in the marble specimens. Since it is very difficult to obtain specimens including natural flaws, we used mechanical method to make a notch in the intact marble. The length of the preset crack (notch) was 4 mm which complied with the standards of fracture toughness testing (Tada et al., 2000). For the intact specimen, the fracture locations are randomly distributed, mainly related to rock heterogeneity and mineral particle size difference. In fact, cracks can easily propagate due to stress concentration effect at the preset notch. In addition, the failure of notched specimens can be compared with that of intact specimens. Fig. 4 and Table 2 show the testing results of pre-notched specimens. It can be seen that the bearing capacity of notched specimens significantly decreases, approximately by 5—10 times that of intact specimens, and the fracture energy is also very low. However, residual strength remains after the peak load due to the presence of pre-existing notch that can improve the plastic properties of rock specimen. The plastic deformation characteristics of Baishan marble with preset notch are dominant, as shown in Fig. 4c. This means that for cracked marble specimen, its resistance capacity decreases due to the presence of cracks. However, it also has strong plastic deformation behaviors after the peak load, and the released energy due to fracture is very low. Though rock specimen is easy to fracture, its plastic deformation is evident.

Because of the complexity of rock material components, there are no standards that have been generally accepted in respect to the three-point bending test for fracture toughness of rock. Hence, this paper adopted the formula obtained from the three-point bending tests on metal materials to calculate the fracture toughness of rock. For three groups of marble specimens using the same criterion/formula, the comparison results will not be significantly varied.
when the unified calculation formula is used. Herein, the formula of fracture toughness obtained from short-span three-point bending tests is selected (Liu, 1994):

\[ K_{IC} = \frac{P_{max}}{bh^{1/2}} Y(a/h) \]  

(6)

where \( P_{max} \) is the load at failure, \( Y(a/h) \) is a function of size, \( b \) is the specimen thickness (5 mm), and \( h \) is the specimen height (10 mm). The effective beam span is 20 mm, equivalent to 2\( h \), less than 4\( h \). Since, the crack length is equal to 0.4\( h \), the function \( Y(a/h) = 7.43 \) (Liu, 1994). Thus, the fracture toughness of Jinping marble under the three-point bending test can be calculated as illustrated in Table 2.

Table 2 shows the final crack propagation path and fracture surface of typical Jinping marbles obtained using laser scanning system. For intact marble, the crack propagation path is zigzag, and the crack opening is larger, which is induced by sudden release of the accumulated elastic energy when severe damage occurs in the marble. But the crack propagation path in Yantang marble of group A1 is 1.3—2.5 times that of marble of group A2, and 1.5—2.5 times that of Baishan marble. The lower resistance to tension and fracture toughness of Baishan marble can be explained as follows:

4. Meso-failure mechanism of Jinping marble

The mechanical and fracturing behaviors of Baishan marbles using the tests mentioned above are significantly different from those of Yantang marbles. One of the reasons is the difference in mineral composition of marble, and the other is the presence of the bedding plane. Table 3 shows the final crack propagation path and fracture surface of typical Jinping marbles obtained using laser scanning system. For intact marble, the crack propagation path is zigzag, and the crack opening is larger, which is induced by sudden release of the accumulated elastic energy when severe damage occurs in the marble. But the crack propagation path in Yantang marble of group

\[ \text{Table 1} \]

<table>
<thead>
<tr>
<th>Jinping marble</th>
<th>Specimen No.</th>
<th>Maximum deflection (mm)</th>
<th>Peak load (N)</th>
<th>Maximum bending stress (MPa)</th>
<th>Peak fracture energy (kN mm)</th>
<th>( E ) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yantang marble (group A1)</td>
<td>A1-01</td>
<td>0.0777</td>
<td>501.8</td>
<td>30.106</td>
<td>18.16</td>
<td>2057.16</td>
</tr>
<tr>
<td></td>
<td>A1-02</td>
<td>0.0454</td>
<td>449.9</td>
<td>26.993</td>
<td>9.25</td>
<td>3516.88</td>
</tr>
<tr>
<td></td>
<td>A1-03</td>
<td>0.0465</td>
<td>541.5</td>
<td>32.491</td>
<td>11.99</td>
<td>4754.8</td>
</tr>
<tr>
<td></td>
<td>A1-04</td>
<td>0.0491</td>
<td>497.5</td>
<td>29.853</td>
<td>11.63</td>
<td>4509.2</td>
</tr>
<tr>
<td></td>
<td>A1-05</td>
<td>0.0411</td>
<td>485.7</td>
<td>29.4</td>
<td>10.25</td>
<td>4902.8</td>
</tr>
<tr>
<td>Yantang marble (group A2)</td>
<td>A2-01</td>
<td>0.0356</td>
<td>280.8</td>
<td>16.851</td>
<td>4.81</td>
<td>3155.2</td>
</tr>
<tr>
<td></td>
<td>A2-02</td>
<td>0.0301</td>
<td>263.7</td>
<td>15.821</td>
<td>4.14</td>
<td>3575.32</td>
</tr>
<tr>
<td></td>
<td>A2-03</td>
<td>0.0353</td>
<td>322.4</td>
<td>19.343</td>
<td>5.6</td>
<td>3706.76</td>
</tr>
<tr>
<td>Baishan marble (group B)</td>
<td>B-02</td>
<td>0.0444</td>
<td>173.8</td>
<td>10.43</td>
<td>3.74</td>
<td>1769.2</td>
</tr>
<tr>
<td></td>
<td>B-03</td>
<td>0.0234</td>
<td>221.1</td>
<td>13.265</td>
<td>4.06</td>
<td>2163.92</td>
</tr>
<tr>
<td></td>
<td>B-04</td>
<td>0.0359</td>
<td>252.8</td>
<td>15.168</td>
<td>4.93</td>
<td>3144.88</td>
</tr>
<tr>
<td></td>
<td>B-05</td>
<td>0.0417</td>
<td>171.2</td>
<td>10.271</td>
<td>4.07</td>
<td>1534.88</td>
</tr>
<tr>
<td></td>
<td>B-06</td>
<td>0.0385</td>
<td>235.5</td>
<td>14.129</td>
<td>4.72</td>
<td>2637.2</td>
</tr>
</tbody>
</table>

\[ \text{Table 2} \]

<table>
<thead>
<tr>
<th>Jinping marble</th>
<th>Specimen No.</th>
<th>Maximum deflection (mm)</th>
<th>Peak load (N)</th>
<th>Maximum bending stress (MPa)</th>
<th>Peak fracture energy (kN mm)</th>
<th>( E ) (MPa)</th>
<th>Fracture toughness ( \left( \text{N mm}^{-3/2} \right) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yantang marble (group A1)</td>
<td>A1-11</td>
<td>0.0215</td>
<td>154.5</td>
<td>9.269</td>
<td>1.8</td>
<td>13,063</td>
<td>72,60178</td>
</tr>
<tr>
<td></td>
<td>A1-12</td>
<td>0.0188</td>
<td>164.1</td>
<td>9.844</td>
<td>1.78</td>
<td>14,970</td>
<td>77,11296</td>
</tr>
<tr>
<td></td>
<td>A1-13</td>
<td>0.0196</td>
<td>130.5</td>
<td>7.833</td>
<td>1.55</td>
<td>10,690</td>
<td>61,32384</td>
</tr>
<tr>
<td>Yantang marble (group A2)</td>
<td>A2-11</td>
<td>0.0112</td>
<td>74.7</td>
<td>4.482</td>
<td>0.562</td>
<td>9753</td>
<td>35,10261</td>
</tr>
<tr>
<td></td>
<td>A2-12</td>
<td>0.0161</td>
<td>86.3</td>
<td>5.179</td>
<td>0.816</td>
<td>10,654</td>
<td>40,55362</td>
</tr>
<tr>
<td></td>
<td>A2-13</td>
<td>0.0175</td>
<td>98</td>
<td>5.883</td>
<td>1.09</td>
<td>10,161</td>
<td>46,05162</td>
</tr>
<tr>
<td>Baishan marble (group B)</td>
<td>B-11</td>
<td>0.0195</td>
<td>84.8</td>
<td>5.087</td>
<td>1.06</td>
<td>1523</td>
<td>39,84875</td>
</tr>
<tr>
<td></td>
<td>B-12</td>
<td>0.0169</td>
<td>63.8</td>
<td>3.827</td>
<td>0.807</td>
<td>2041</td>
<td>29,98054</td>
</tr>
<tr>
<td></td>
<td>B-13</td>
<td>0.0226</td>
<td>65.7</td>
<td>3.945</td>
<td>1.04</td>
<td>858</td>
<td>30,87338</td>
</tr>
<tr>
<td></td>
<td>B-14</td>
<td>0.0242</td>
<td>71.5</td>
<td>4.292</td>
<td>1.2</td>
<td>1199</td>
<td>33,90888</td>
</tr>
</tbody>
</table>

Fig. 4. Load-deflection curves of Jinping marble with preset notch.
A1 is more complicated than that of group A2 due to the poor tensile performance of bedding plane. In other words, damage develops along the bedding plane when the direction of tensile stress is perpendicular to the bedding plane. Therefore, the crack propagation path is basically straight, and the fracture surface is relatively flat. For pre-notched marbles, there are a large number of microcracks at the tip of main crack, and few in the marble of group A1 but more in the marble of groups A2 and B are observed. The presence of microcracks will consume part of surface energy which yields low bearing capacity of marble with pre-existing notch. But the plastic characteristics of rock after the peak load cannot be ignored. The surface height of marbles of groups A2 and B ranges around from 0 to 0.4 mm, while 0–1 mm for the marble of group A1. It suggests that the fracture surface of marbles of group A1 is rougher, which can be used to account for the energy dissipation mechanism.

5. Fractal characteristics of fracture morphology of Jinping marble

After the tests, the fracture morphology of rock specimens has been measured by SEM and shown in Table 3. The cube covering method was adopted to calculate the fractal dimension of surface morphology. The results are shown in Fig. 5 where \( \delta \) is the covering scale, and \( x(\delta) \) is the corresponding covering area. The fitting coefficient is 0.9985–0.9997, as shown in Fig. 5. For the Jinping marble at meso-scale, the fractal dimension of Yantang marble of group A1 is statistically the largest, and that of Baishan marble is the smallest, as shown in Fig. 6. It means that the Yantang marble of group A1 is the roughest and more energy is consumed when the specimen fractures. Conversely, the fracture surface of Yantang marble of group A2 is relatively flat and little energy is consumed. Fig. 6 indicates that the fractal dimensions of different Jinping marbles are significantly varied. In addition, it suggests that the fractal dimension can be used to roughly represent the characterization of fracture morphology after failure of material.

6. Conclusions

This paper intends to study meso-failure mechanism and fracture morphology of Jinping marble using SEM with loading system. The main conclusions can be drawn as follows:
The fracture toughness and elastic modulus of Yantang marble are higher than those of Baishan marble, which can be attributed to different mineral components and a small content of mica in Baishan marble. The Yantang marble has strong brittle failure characteristics. However, the Baishan marble has the nature of slight ductility. Therefore, potential risk of rockburst in Yantang marble is higher.

The direction of tensile stress on bedding plane has a major effect on the mechanical behaviors and fracture toughness of marble. The average peak load and fracture toughness of Yantang marble

Fig. 5. Fractal dimensions of fracture morphology in Jinping marbles.
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Fig. 6. Comparison of fractal dimension of fracture morphology in Jinping marbles.

(group A1) are 1.4–2.1 and 1.3–2.2 times those of Yantang marble (group A2), respectively. The crack in Yantang marble of group A2 basically propagates along the bedding plane, and the propagation path is linear approximately. Since the direction of tensile stress is parallel to the bedding plane in the marble of group A1, both the crack path and fracture morphology are rough, which is the main source of energy consumption.

(3) For the marble with pre-existing notch, a large number of microcracks at the tip of main crack are observed in Yantang marble of group A1 and Baishan marble. However, few microcracks occur around the main crack tip in Yantang marble of group A2. Therefore, one of the weakening mechanisms of Jinping marbles is the propagation of a large number of microcracks at the tip of main crack.

(4) The average bearing capacity of intact marble is 3.4 times that of marble with pre-existing notch, even though the ductility property of defective marble after peak load is better than that of intact marble. Therefore, larger deformation of marble with pre-existing notch than intact marble occurs before failure at Jinping II hydropower station.

(5) The fracture morphology was measured after failure of Jinping marble and the fractural dimensions were calculated using the cube covering method. The largest fractal dimension comes from Yantang marble with tensile stress parallel to bedding plane. The fracture morphology is the roughest and more energy is consumed when the specimen is fractured. However, the fracture surface of Yantang marble with tensile stress vertical to bedding plane is relatively flat and little energy is consumed at fracturing.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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