Bench Blasting Excavation Test for Multifault Foundation Pit of DG Hydropower Station

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Abstract: A DG hydropower station is studied in a high-altitude area, where the air is thin and a fault fracture zone develops on the left and right banks of the dam foundation and riverbed dam section. To ensure the quality of the foundation pit blasting excavation and reduce the blasting disturbance to the surrounding unexcavated rock mass, a bench blasting excavation test is conducted on the dam foundation and the relaxation depth detection is adopted for the foundation rock blasting excavation. The average attenuation rate of acoustic wave velocity before and after blasting of all control points of rock mass meets the relevant standards and specifications, and the overall performance of excavation and cleaning is good. Test results show that reasonable blasting parameters are favorable for the formation of foundation excavation, and this technology can be used as a reference in similar projects.

1. Introduction
China’s hydropower energy industry has considerably developed in more than 40 years because of reformation and opening-up policy. With the continuous growth of hydropower-installed capacity, the hydropower-installed capacity and power generation of China now rank first in the world. Hydropower projects in the middle and lower reaches of rivers and in relatively convenient geographical locations in China are almost complete. Therefore, the focus of hydropower industry has shifted to the middle and upper reaches of rivers in southwest China, where resources have not been fully exploited. Many restrictive factors are implemented because this location is close to the Tibetan area, whose ecological environment is fragile and difficult for development.

The blasting excavation of rock mass is a complex, dynamic process. Different blasting methods will have different effects on the excavation face and cause different degrees of damage to the retained rock mass. Blasting excavation and blasting vibration control technology have always been a challenge in blasting and geotechnical engineering. Researchers all over the world have studied blasting excavation and blasting vibration of rock mass extensively, summarizing numerous results after long-term exploration. Air interval charging blasting technology can achieve a similar effect as the conventional charging method and reduce charging workload and the use of initiating equipment considerably, thus improving work efficiency and saving blasting cost. Under the special climate conditions in the Tibetan area, the air interval charging technology is adopted, and optimal blasting parameters are selected through a blasting test. The relaxation depth of rock mass before and after excavation is tested to ensure blasting quality by determining the blasting relaxation depth and influence zone, as well as to further provide basic data for foundation surface acceptance inspection of riverbed dam foundation. Good blasting fragmentation can improve the efficiency of mechanical excavation and speed up the construction progress.
2. Overview
Located in the Shannan Prefecture of the Tibet Autonomous Region, the DG hydropower station is a second-class large Type (2) project whose major development task is power generation. The normal reservoir water level is 3447.00 m, with a corresponding storage capacity of 552.8 million m³. The control catchment area in the dam site is 15.74 million km², with an average annual flow of 1010 m³/year and installed capacity of 660 MW.
The DG hydropower station’s location has a high altitude (dam crest elevation: EL3451.00 m), low air pressure (annual average air pressure: 685.5 hpa), dry climate (average relative humidity for years is 51%), thin air, and adverse construction environment, which directly affects the efficiency and effect of blasting construction.
The lithology of the dam foundation surface is biotite granodiorite, which is strongly weathered and has many fault fracture zones. The joint surfaces of low-angle fissure developed with fracture, which is in the inset-block fracture structure, and the lithology integrity is poor.

![Figure 1](image)

**Figure 1.** Experts from the China Renewable Energy Engineering Institute inspecting the geological conditions of the site.

3. Test Site and Parameter Design

3.1. Test Site Selection
According to the excavation progress and structural arrangement of each working face, the blasting test site is Platform EL.3345 of Block 5# on the left bank. The test site is 24-m long and 9.2-m wide, with a blasting excavation depth of 5 m. The total test site area is 220.8 m². A pioneer trench (24-m long × 4-m wide × 5.5-m high) is excavated before the test to facilitate drilling and blasting.
3.2. **Blasting Test Parameters**

To protect the rock mass in the conservation area from the influence of blasting vibration in the evacuation area, the blasting is conducted on the surrounding contour using controlled blasting technology, i.e., presplitting blasting and smooth blasting. These two technologies are widely used in blasting excavation engineering. However, different opinions exist as to which technology is less damaging to the retained rock mass, and a conclusion cannot be reached owing to different engineering conditions.

Practical experience has shown that presplitting blasting causes greater damage to rock mass in the conservation area than smooth blasting does. However, the influence of blasting on the main blasting area is related to the effect of presplitting, and proper presplitting may induce lower vibration of the main blasting area than smooth blasting does. Therefore, blasting parameters need to be designed in advance. According to the special climate and geological conditions of the construction site, two contour blasting technologies—presplitting or smooth blasting—are adopted at the excavation contour of rock mass to reduce the damage and vibration of rock excavation blasting on the bearing rock mass. Air interval and uncoupled charging are adopted to control the blasting pressure and reduce the blasting damage.

3.2.1. **Vertical Shallow Hole Bench blasting + Layered Smooth Blasting with Horizontal Pre-reserved holes**

Smooth blasting is a type of controlled blasting technology that is flat with a new wall face and causes no obvious damage. It involves drilling a row of smooth blasting holes on the designed excavation contour line that matches the minimum resistance line, and an uncoupled charge or other special charging structure is used. After the main excavation body is blasted, the charge in the smooth blasting holes is detonated, forming a flat, smooth excavation surface through the smooth blasting hole. Blasting excavation is conducted twice according to the established excavation depth. The blasting flowchart is shown in Figure 3, and the blasting parameters are shown in Table 1.
Figure 3. Flowchart of smooth blasting.

Table 1. Vertical shallow hole bench blasting + parameters of layered smooth blasting with pre-reserved horizontal smooth face.

| Name of the hole | Drilling parameters | Charging parameters | Number of holes (pcs.) | Amount of charging (kg) | Form of charging |
|------------------|---------------------|----------------------|------------------------|------------------------|-----------------|
|                  | Hole diameter (mm)  | Hole pitch (cm)      | Hole depth (cm)        | Charging diameter (mm) | Single-hole dose (kg) | Charging density (g/m) | Plug length (cm) | |
| Vertical blasting holes in main blasting layer | 90 | 200/220 | 300 | 70 | 6 | / | 150 | 22 | 132 | Continuous charging |
| Horizontal main blasting holes for protective cover | 70 | 150/180 | 920 | 32 | 7.8 | / | 140 | 8 | 62.4 | Continuous charging |
| Horizontal pre-reserved holes of smooth blasting for protective layer | 70 | 60/75 | 920 | 32 | 1.7/1.95 | 185/212 | 80 | 19 | 31.15 | Air interval charging |

3.2.2. Horizontal Presplitting Holes + Vertical Shallow Hole Bench Blasting Technology

In presplitting blasting, a through crack with a certain width is formed along the design contour line before blasting, followed by drilling blasting work in the excavation area. The cracks separate the rock mass in the excavation and conservation areas. Thus, the stress wave in the excavation area reflects and refracts on the fracture surface, thus greatly weakening the stress wave intensity that passes through it. Therefore, this process can control the damage of rock mass in the retained area, protect buildings in the area, reduce overexcavation, and accelerate the construction progress, which is why it has been widely promoted and adopted all over the world.

According to the established excavation depth, blasting excavation is conducted only once. The blasting flowchart is shown in Figure 4, and the blasting parameters are shown in Table 2.
3.3. Blasting Network Design

The blasting network is initiated by adopting delayed initiation in the hole and delayed transmission outside the hole. A detonation cord is used to connect the blasting network, and the detonating network is facilitated by an electric detonator.

In the design of the blasting network, the detonation transmission outside the main blasting hole should be completed before the presplitting hole is detonated to reduce misfire factors. The detonation cord is used to initiate the presplitting blasting. When being blasted with the main blasting hole, the presplitting hole is blasted 150 ms ahead of the main blasting hole. The initiation time of the presplitting blasting hole before the adjacent bench blasting hole is more than 75–100 ms. In the test, the initiation time of the presplitting hole is 150 ms ahead of the bench blasting hole.

3.4. Drilling and Charging Craft Test

According to the uncovered excavated rock strata, the faults and joints of the foundation rock body of the dam are developed, in which the left bank downstream rock mass is relatively complete and the right bank rock body is weakly weathered. Some areas of the upstream overflow dam section are mainly drifting cobbles and pebbles. According to the geological lithological characteristics of the project, this test mainly focuses on the suitable drilling machine and charging technology for the optimum drilling depth, hole diameter, and inclination angle under the geological conditions. In accordance with the field drilling test results, a down-the-hole driller and a pneumatic driller that do not become stuck easily should be adopted for the part with good surrounding rocks. A hydraulic driller with a high drilling efficiency and smooth drilling should be adopted for parts with broken rocks. The down-the-hole drilling and pneumatic drilling usually take a long time to set up the sample.
frame when drilling and have relatively low efficiency. The hydraulic driller should be used as much as possible when drilling the main blasting hole, thus allowing time for down-the-hole drilling and pneumatic drill to conduct structural edge presplitting drilling. The hydraulic driller is used to drill holes in areas with poor surrounding rocks, where it can easily become stuck. Before charging, the dust in the hole is removed, and the cartridge is loaded from bottom to top according to the blasting design. The initiating body is installed within a one-third range of the hole bottom, and reverse initiation mode is adopted. The main blasting hole is continuously charged, and the presplitting hole and pre-reserved holes of smooth blasting are charged by air interval.

### 3.5. Test Group

According to the actual construction situation in the site, the blasting test is divided into four groups in accordance with the preliminary parameters of the blasting design. The parameters are shown in Table 3.

**Table 3. Parameters for blasting test groups.**

| Group      | Hole pitch                                     | Charging parameters                                 | Note                        |
|------------|------------------------------------------------|-----------------------------------------------------|-----------------------------|
| Group 1    | (1) Pitch of the vertical blasting holes of the main blasting layer is 2 m; (2) Pitch of the horizontal main blasting holes of the protective layer is 1.5 m; (3) Hole pitch of smooth blasting of the protective layer is 0.6 m; | Single-hole charging for horizontal holes of smooth blasting is 1.7 kg; |                           |
| Group 2    | (1) Pitch of the vertical blasting holes of the main blasting layer is 2.2 m; (2) Pitch of the horizontal main blasting holes of the protective layer is 1.8 m; (3) Hole pitch of smooth blasting of the protective layer is 0.75 m; | Single-hole charging for horizontal holes of smooth blasting is 1.95 kg; |                           |
| Group 3    | (1) Pitch of vertical blasting holes is 2 m; (2) Pitch of the horizontal presplitting holes is 0.6 m; (1) Pitch of the vertical blasting holes is 2.2 m; | Single-hole charging for horizontal presplitting holes is 1.95 kg; |                           |
| Group 4    | (2) Pitch of the horizontal presplitting holes is 0.75 m; | Single-hole charging for horizontal presplitting holes is 2.25 kg; |                           |

### 4. Blasting Test Results

The on-site blasting test is conducted according to the test groups, and the blasting effects are shown in Table 4.

**Table 4. Statistics for the effect of blasting test.**
| Test item               | Group 1       | Group 2       | Group 3       | Group 4       | Note                                  |
|------------------------|---------------|---------------|---------------|---------------|---------------------------------------|
| Residual porosity ratio| 85.5%         | 75.2%         | 65.2%         | 68.9%         |                                       |
| Maximum unevenness     | No            | No            | No            | No            |                                       |
| Under-excavation       | No            | No            | No            | No            |                                       |
| Rock wall              | Generally flat| Generally flat| Rough and uneven in some parts, comparatively flat | Rough and uneven in some parts, comparatively flat |                                       |
| Blasting crack         | No            | No            | No            | No            |                                       |

**Figure 5.** Effect of blasting excavation for group 1.
The inspection is summarized as follows according to the residual porosity of the rock face after blasting, the flatness of the rock face, and the intactness of the residual hole’s walls:

1. The comparison between the effect of vertical shallow hole bench blasting + layered smooth blasting with horizontal pre-reserved holes and horizontal prestripping hole + vertical shallow hole bench blasting indicates that vertical shallow hole bench blasting + layered smooth blasting with horizontal pre-reserved holes is significantly better.

2. When the online charging density is 185 g/m and the pitch of the holes is 60 cm, the rock wall surface between the two adjacent holes after blasting is flat overall. The surrounding rock of this part is poorly located; thus, the hole traces are evenly distributed on the excavation contour.

3. When the online charging density is 212 g/m and the pitch of the holes is 75 cm, the rock wall surface between two adjacent holes is smooth overall except for some local unevenness after blasting. Moreover, blasting hole marks are evenly distributed on the excavation contour with the ideal overall blasting effect.

In sum, a hole distance of 70 cm can be set as an excavation parameter of smooth blasting, and the charging density of the hole line should be controlled at about 190–200 g/m. The geological conditions greatly influence the blasting quality. Therefore, during the excavation of the protective layer, the formation of the excavated part and the geological conditions of the excavation of the protective layer need to be taken into account, summarizing the experience in time and optimizing the blasting parameters to improve the excavation quality.

5. Blasting Relaxation Depth

5.1. Overview

The attenuation rate of the acoustic wave velocity of the in-situ test hole in the rock mass of the foundation plane before and after excavation of the protective layer is tested to determine the relaxation depth and influence zone of the excavation and blasting of the rock mass. This process provides basic data for foundation surface acceptance inspection of riverbed dams, which is an
important basis for evaluating the depth of the blasting relaxation circle after excavation. Moreover, this serves as important basic information for the consolidation grouting of dam foundation. According to the technical requirements, the attenuation rate of wave velocity of rock mass in the foundation surface of each building before and after blasting is not more than 10%. The thickness of the relaxation layer is judged by the obvious inflection point of the wave velocity after blasting.

5.2. Test Principle
The operation diagram of the single-hole acoustic wave test, which is also called acoustic velocity logging, is shown in Figure 7. A single-hole acoustic probe is used to test the acoustic velocity every 20 cm in the borehole, and a wave velocity curve that varies with depth along the borehole direction from the hole opening to the hole bottom is obtained. The acoustic P-wave velocity measured by this method mainly reflects the quality of the rock mass near the borehole wall.[10]

Figure 7. Single-hole acoustic wave working diagram.

The HX-SY02A multifunctional acoustic wave instrument from Yueyang Aocheng Technology Co., Ltd. and ZBL-U5700 multifunctional acoustic wave instrument from Beijing Zhibolian Technology Co., Ltd. are used to test single-hole acoustic in this work area. The number of sampling channels is 2, the sampling interval is 0.1 μs, the acoustic measurement accuracy is ±0.1 μs, and the pass frequency width is 10–200 kHz. The field test requirements are as follows:

(1) The borehole is filled with clean water, and the borehole is checked to ensure that it is unimpeded prior to testing.

(2) According to the distance between the transmitter and the receiver, the delay time of the acoustic instrument is set to 20–40 μs so that the first acoustic wave is located in the middle of the display. The sampling points are 1024, full-pass filtering is used, the waveform is saved, and a transmission voltage of 1000 V is applied.

(3) The continuous transmission method is adopted during sampling. After the amplitude, sound time, and frequency stabilized, the disk is saved to finish the detection of the measuring point;

(4) The distance between the acoustic testing points of a single hole is 0.2 m, and the depth is checked once every 1 m;

(5) The remeasurement workload is not less than 10%, and the sound measurement error is not more than 5%.

5.3. Single-hole Acoustic Test Results

5.3.1. Wave Velocity Statistics
The wave velocity statistics on the basis of the test results before and after blasting are shown in Table 5.

**Table 5. Statistical table of wave velocity before and after blasting.**

| Number | Hole depth (m) | Pre-explosion wave velocity (m/s) | Post-explosion wave velocity (m/s) | Attenuation rate (%) |
|--------|---------------|-----------------------------------|-----------------------------------|----------------------|
| 1      | 0.2           | 4520                              | 4100                              | 9.3                  |
| 2      | 0.4           | 4610                              | 4230                              | 8.2                  |
| 3      | 0.6           | 4420                              | 4180                              | 5.4                  |
| 4      | 0.8           | 4450                              | 4320                              | 2.9                  |
| 5      | 1.0           | 4440                              | 4390                              | 1.1                  |
| 6      | 1.2           | 4640                              | 4600                              | 0.9                  |
| 7      | 1.4           | 4370                              | 4370                              | 0.0                  |
| 8      | 1.6           | 4450                              | 4450                              | 0.0                  |
| 9      | 1.8           | 4310                              | 4310                              | 0.0                  |
| 10     | 2.0           | 4500                              | 4480                              | 0.4                  |
| 11     | 2.2           | 4450                              | 4500                              | −1.1                 |
| 12     | 2.4           | 4450                              | 4410                              | 0.9                  |
| 13     | 2.6           | 4240                              | 4400                              | −3.8                 |
| 14     | 2.8           | 4500                              | 4380                              | 2.7                  |
| 15     | 3.0           | 4530                              | 4500                              | 0.7                  |

The average wave velocity of each hole section after blasting increases with the hole depth, and the average value of each hole section is greater than 4050 m/s.

5.3.2. Depth of Blasting Relaxation Zone
The blasting relaxation depth for each test hole is shown in Table 6.

**Table 6. Excavation and blasting relaxation depth testing results for foundation rock.**
5.4. Blasting Relaxation Depth Results
Within a 1-m range from the foundation surface, the average attenuation rate of acoustic wave velocity of rock mass in the blasting test area before and after blasting is less than 10%, which meets the design requirements and is considered normal blasting relaxation damage. Below 1 m in the blasting test area, the average attenuation rate of the acoustic wave velocity of rock mass in each hole section before and after blasting is less than 10%, which meets the design technical requirement. Overall, the blasting test parameters meet the requirements.

6. Blasting Safety
During blasting tests, the following formula is required to calculate the distance of the blasting flying stone\(^{[11]}\):

\[
R_f = 20K_f n^2 W \quad (1)
\]

where

- \(R_f\) is the safety distance for the blasting operator from a flying stone;
- \(n\) is the blasting action index, which is considered as 0.75 according to the loose blasting control;
- \(W\) is the minimum resistance line, m; and
- \(K_f\) is the safety factor; generally, \(K_f = 1\) to 1.5 is chosen and \(K_f = 1.5\) is considered.

During the blasting test, the safety distance of flying stones in different blasting holes is calculated as follows.

| Hole no. | Dam section | Average attenuation rate (%) | Relaxation depth (m) |
|----------|-------------|-----------------------------|----------------------|
| BP30     | Dam Section No. 5 | 0–1 m | 1–2 m | 2–3 m | 3–5 m | 5–10 m | 0.3 | −0.1 | 0.1 | 0.1 | 1.2 |

**Table 7. Safety distance for blasting flying rock.**

| Type of blasting                     | Line of resistance W (m) | Rf (m) safety distance from a flying stone | Note                                           |
|--------------------------------------|--------------------------|------------------------------------------|------------------------------------------------|
| Main blasting hole                    | 1.2                      | 20.25                                    | /                                              |
| Presplitting hole                     | 0.8                      | 13.5                                     | Consider only the resistance line at the top of the charge (plugging section). |
| Pre-reserved holes of smooth blasting | 0.8                      | 13.5                                     | /                                              |

7. Conclusions
Smooth blasting is adopted for excavation in a high-altitude area based on the analysis of four groups of blasting test results. A distance of 70 cm between the smooth blasting holes is selected. The charging density of the hole line is controlled at 190–200 g/m. The air interval and uncoupled charging are adopted. The blasting excavation effect is ideal, and the charging workload is reduced. The blasting relaxation depth detection shows that the attenuation rates of the wave velocity of the rock mass in the foundation surface before and after blasting are no more than 10%. Therefore, the blasting effect is good and meets the design requirements, and this approach can be used as a reference in similar projects.
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