Dam foundation excavation techniques in China: A review

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A B S T R A C T

A protective layer (PL) is commonly reserved above foundation surface to protect the underlying rock mass during dam foundation excavation. In China, the PL of dam foundation is conventionally subdivided into two or three thin layers and excavated with the shallow-hole blasting method, even by pneumatic pick method in case of soft rock mass. The aforementioned layered excavation of the PL delays the construction of the whole project. After nearly 30-year practices, several safe and efficient methods for the PL excavation of dam foundation are gradually developed. They include shallow-hole bench blasting with cushion material (SBC) at the bottom of the hole, and horizontal smooth blasting (HSB). The PL is even cancelled on the condition that horizontal pre-split technique is employed during dam foundation excavation. This paper introduces the aforementioned two PL excavation methods (shallow-hole blasting and bench blasting) and horizontal pre-split technique of dam foundation without protective layer (HPP). The basic principles of blasting method, blasting geometry, charge structure, drill-and-blast parameters of typical projects are examined. Meanwhile, the merits and limitations of each method are compared. Engineering practices in China show that HSB is basically the optimal method for dam foundation PL excavation in terms of foundation damage control and rapid construction. Some new problems for dam foundation PL excavation arising, such as strong unloading and relaxation phenomenon that encountered in the gorge region of southwest China, are needed to be addressed; and the corresponding countermeasures are discussed as well.

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1. Introduction

With the rapid development of economy, a sharp increasing demand for electricity is required in China in the last three decades. As a result, many large-scale hydropower projects have been completed or are under construction in China [Jia et al., 2010], as shown in Table 1. Construction of hydropower projects often involves large-scale and high-intensity excavation, whilst drill-and-blast method is still the main method for rock dam foundation excavation. The dam foundation surface serves as the bearing surface, and it should be noted that water pressure is acting on the bedrock where the weak interfaces between the dam and the bedrock are observed. Therefore, the stabilities of the reservoir-dam system and the bedrock are critically important during dam foundation excavation by blasting. In the process of dam foundation excavation, weathered and other weak rocks need to be fragmented by blasting and removed. Meanwhile, blasting-induced damage should be strictly controlled, especially in the regions in the vicinity of the designed excavation contours such as the foundation surface. Hence, close attention has been paid to blasting techniques which are employed on dam foundation surface.

Generally, the following four steps are taken during dam foundation excavation, i.e. (1) removing the loose rock mass before excavation, (2) excavating the main rock body at a certain distance above the planned foundation level, (3) excavating reserved rock mass near the planned foundation level, and (4) cleaning the foundation (Murphy et al., 1976; Novozhilov and Oganesyan, 1978; Mgolabelov, 2000; Küehnel, 2004).

In Europe and USA, the main rock body at a certain distance above the planned foundation level is usually excavated by loosening blasting method combined with controlled perimeter blasting techniques, such as pre-splitting, cushion blasting or smooth blasting. The selection of specific blasting method and thickness of the reserved rock mass are generally left to the contractor. The reserved rock mass near the planned foundation level is usually excavated by shallow-hole blasting or prying with hydraulic excavator.

In the former Soviet Union, during the dam foundation excavation process, a protective layer (PL) above the designed foundation
surface must be reserved. The main body of the rock mass is excavated by bench blasting, and the PL will be excavated by the controlled perimeter blasting. In China, this former Soviet Union’s method was adopted in dam foundation excavation before 1980s. Typical dam foundation excavation method is shown in Fig. 1.

The thickness of the PL is determined associated with the geometry of blasting-induced damage zone (BDZ). The BDZ is generally defined as the rock zone beyond the excavation boundary where the physical, mechanical and hydraulic properties of the rock mass have been significantly affected due to blasting excavation (Cai and Kaiser, 2005; Blümling et al., 2007; Malmgren et al., 2007; Wu et al., 2009; Bastante et al., 2012). The larger the BDZ is, the thicker the PL is. In gorge regions with high in situ stress, rapid excavation of rock mass will lead to a quick release of in situ stress that induces an excessive deformation and a bigger excavation-induced damage zone (EDZ) during dam foundation excavation (Li et al., 2010; Duan et al., 2011; Chen et al., 2012).

According to the Construction Technical Specifications on Rock Foundation Excavating Engineering of Hydraulic Structures in China (DLT5389-2007), the thickness of the PL in the vicinity of the horizontal foundation surface should be determined by in situ blasting test. If an in situ blasting test is difficult to perform, a thickness of 25–40 times the cartridge diameter \( D \) of the last layer for bench blasting is proposed, as shown in Table 2. The thickness of dam foundation PL of some newly constructed large-scale projects (Luo and Shen, 2003; Bao and Wan, 2006; Zhao et al., 2008; Guan and Yuan, 2009) is listed in Table 3.

### Table 1
Statistics of dam construction in China.

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of dams</th>
<th>Proportion all over the world (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dam height &gt;30 m</td>
<td>Dam height &gt;100 m</td>
</tr>
<tr>
<td>1973</td>
<td>1644</td>
<td>14</td>
</tr>
<tr>
<td>1988</td>
<td>3768</td>
<td>33</td>
</tr>
<tr>
<td>2005</td>
<td>4839</td>
<td>129</td>
</tr>
<tr>
<td>2008</td>
<td>5191</td>
<td>142</td>
</tr>
</tbody>
</table>

### 2. Layered excavation of dam foundation protective layer

The layered blasting excavation of the PL has been employed in China for several decades since 1960s. In the current technical standard DLT5389–2007, the conventional layered blasting excavation is still suggested as a reliable method for dam foundation PL excavation. The 3-layer PL excavation should be considered, and the excavation of each layer is strictly controlled. Typical procedure of layered blasting excavation of PL is shown in Fig. 2.

1. **The first layer**

   Shallow-hole bench blasting should be adopted. After the excavation of the first layer, the remaining thickness of the PL should be not less than 1.5 m. Cartridge diameter should be less than 40 mm.

2. **The second layer**

   For the second layer, the single-hole blasting method should be adopted. After the excavation of the second layer, for intact/hard or relatively intact/hard rock mass, the remaining thickness should be not less than 0.5 m; for jointed/soft rock mass, the remaining thickness should be not less than 0.7 m. The angle between the drilling hole and the horizontal foundation surface should be not less than 60°. Cartridge diameter should be less than 32 mm.

3. **The third layer**

   For intact/hard or relatively intact/hard rock mass, the drilling hole should not go through the horizontal foundation surface; for jointed/soft rock mass, the bottom of drilling hole should be 0.2 m above the horizontal foundation surface, and the final 0.2 m of rock mass should be excavated by prying. The provisions for angle of the drilling hole and cartridge diameter

### Table 2
PL thickness \( H \) proposed in technical specifications by National Development and Reform Commission of People’s Republic of China (2007).

<table>
<thead>
<tr>
<th>Type</th>
<th>Intact and hard</th>
<th>Relatively intact/hard</th>
<th>Jointed and soft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cartridge diameter ( D )</td>
<td>25D</td>
<td>30D</td>
<td>40D</td>
</tr>
</tbody>
</table>

### Table 3
Thickness of dam foundation PL of some newly constructed large-size projects (Luo and Shen, 2003; Bao and Wan, 2006; Zhao et al., 2008; Guan and Yuan, 2009).

<table>
<thead>
<tr>
<th>Project</th>
<th>Thickness of PL (m)</th>
<th>Lithology of dam area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xihaihu</td>
<td>5.5</td>
<td>Breccia lava/basalt</td>
</tr>
<tr>
<td>Jinping</td>
<td>5</td>
<td>Sandy slate/marble</td>
</tr>
<tr>
<td>Laxiwa</td>
<td>3</td>
<td>Metamorphic rock/intrusive granite</td>
</tr>
<tr>
<td>Longtan</td>
<td>3</td>
<td>Sandstone/siltstone/argillite</td>
</tr>
</tbody>
</table>

### Fig. 1
Typical dam foundation excavation method in China.

### Fig. 2
Typical procedure of layered blasting excavation of PL.
and detonating method are the same as those for the second layer.

The idea of bench blasting with shallow-hole and thin-layers is preferable owing to the strict control of the BDZ. However, the construction speed of the PL excavation is significantly reduced due to such a layered excavation method (Zhang, 2003). Different from the general construction projects, hydropower projects usually have a large investment and a long construction period. It is of great significance for the rapid construction of hydropower projects. Engineers and researchers in China have made great efforts to revise the conventional layered excavation method and develop some new methods that are safer and more efficient.

3. New methods for dam foundation protective layer excavation

Production experiments of some excavation methods (shallow-hole bench blasting with cushion at the bottom of hole (SBC), horizontal pre-split of dam foundation without PL (HPP)) had been proposed for some large-size hydropower projects since 1970s. The examples are Gezhouba (Yangtze River, Hubei Province) in 1971 (SBC), Dongjiang (Xiangjiang River, Hunan Province) in 1978 (HPP). However, the first technical standard of dam foundation excavation, i.e. Construction Technical Specifications on Rock Foundation Excavating Engineering of Hydraulic Structures (SDJ211-83) (Ministry of Water Resources and Electric Power of People's Republic of China, 1983) in China, layered blasting was required in PL excavation of dam foundation.

With the progress of theories and practices in engineering, some modifications were made in Construction Technical Specifications on Rock Foundation Excavating Engineering of Hydraulic Structures (SL47-94) (Ministry of Water Resources and Ministry of Electric Power Industry of the People's Republic of China, 1994). In SL47-94, the layered blasting excavation method was recommended, but it also pointed out that blasting methods for dam foundation excavation with or without PL could be adopted if they were proven to be feasible by blasting test. During this period, one-time blasting excavation methods for dam foundation with or without PL were used in many large-scale hydropower projects, such as Longtan (Hongshui River, Guangxi Zhuang Autonomous Region), Xiaowan (Lancang River, Yunnan Province), Gaobazhou (Qingjiang River, Hubei Province), Xiluodu (Jinsha River, Sichuan Province and Yunnan Province), etc., and good engineering and economic benefits have been achieved.

In the current technical standard DLT5389-2007, some new methods, such as SBC, HSB, HPP, are recommended for the first time, as they are proven to be feasible by blasting test, and the layered blasting excavation is just reserved but no longer recommended as the preference method.

Statistics of dam foundation excavation methods for part of the large-scale hydropower projects in China are listed in Table 4.

3.1. Shallow-hole bench blasting with cushion at the bottom of hole

In 1982, the SBC was proposed and then applied to production excavation of dam foundation PL at Wanan hydropower station (Ganjiang River, Jiangxi Province). Since then, this method was employed in several other projects, such as Dongfeng hydropower station (Wujiajiang River, Guizhou Province), Geheyuan hydropower station (Qingjiang River, Hubei Province), first-phase longitudinal cofferdam of the Three Gorges Project (Yangtze River, Hubei Province), etc.

Fig. 3. Schematic diagram of stress wave interaction on the interface of explosive and cushion. $A_i$ is the amplitude of the reflection wave.

3.1.1. Basic principles

The schematic diagram of stress wave interaction on the interface of explosive and cushion is shown in Fig. 3. The stress state of the bedrock beneath the blasting hole can be effectively ameliorated by setting a flexible cushion at the bottom of the blasting hole. Generally, the sonic impedance of cushion material ($\rho_1C_1$) is smaller than that of explosive ($\rho_0C_0$). When the detonation wave strikes the interface of explosive and cushion materials, the reflection and transmission of detonation wave would occur on the interface, and the amplitude of transmitted wave can be written as

$$A_i = \frac{2\rho_1C_1}{\rho_0C_0 + \rho_1C_1}A_0$$

where $A_i$ and $A_0$ are the amplitudes of transmitted wave and incident wave, respectively; $\rho_0$ and $\rho_1$ are the densities of explosive and cushion material, respectively; $C_0$ and $C_1$ are the sound wave velocities of explosive and cushion material, respectively.

As a consequence, the stress wave acting on the bedrock under the borehole is reduced. When the stress is reduced to a value less than the ultimate compressive strength and the ultimate tensile strength of the bedrock, effective protection of the bedrock can be achieved.

3.1.2. Technical points

(1) Reasonable cushion materials with low sonic impedance

Cushion design basically includes three parts, namely the cushion length, the cushion location and the cushion materials. In general, the cushion should be set above the foundation surface, and the cushion length should not be too large in order to avoid excessive blasting toes.

According to the action principle of the cushion, it can be seen that the smaller the wave impedance of cushion materials is, the better protection effect the bedrock will get. Currently, the cushion materials commonly used in projects include sawdust, rock debris, polyethylene foam, bamboo tube, wood, etc. In practice, blasting effect and economic evaluation of different cushion materials will be screened in optimum design. Cushion design parameters of typical projects (Pan, 1994; Xu and Lin, 1999; Zhen, 1999) are shown in Table 5.

(2) Shallow-hole blasting

In shallow-hole blasting, the low bench and the small diameter boreholes are adopted, which is one of the important means to reduce the charge per delay interval and blasting vibration. In engineering practices, the bench height is usually less than 5 m, and the borehole diameter is usually less than 50 mm.

(3) Detonating hole by hole

Detonating hole by hole, namely millisecond delay blasting, which would transform a big charge of blasting into a series
Table 4
Statistics of dam foundation excavation methods for some large-size hydropower projects in China.

<table>
<thead>
<tr>
<th>Project</th>
<th>Dam type</th>
<th>Dam height (m)</th>
<th>Installed capacity (MW)</th>
<th>Storage capacity (10^6 m^3)</th>
<th>Excavation method</th>
<th>Start date</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gezhoua</td>
<td>Concrete gate dam</td>
<td>47</td>
<td>2715</td>
<td>15.8</td>
<td>LB/SBC</td>
<td>1971</td>
<td>Yangtze River, Hubei Province</td>
</tr>
<tr>
<td>Dongjiang</td>
<td>Double curvature arch dam</td>
<td>157</td>
<td>500</td>
<td>81.2</td>
<td>HPP</td>
<td>1978</td>
<td>Xiangjiang River, Hunan Province</td>
</tr>
<tr>
<td>Baozhusi</td>
<td>Gravity dam</td>
<td>132</td>
<td>700</td>
<td>25.5</td>
<td>HPP</td>
<td>1984</td>
<td>Jialing River, Sichuan Province</td>
</tr>
<tr>
<td>Yantan</td>
<td>Gravity dam</td>
<td>110</td>
<td>245</td>
<td>26</td>
<td>SBC</td>
<td>1985</td>
<td>Hongshui River, Guangxi Zhuang Autonomous Region</td>
</tr>
<tr>
<td>Geheyan</td>
<td>Gravity arch dam</td>
<td>151</td>
<td>1200</td>
<td>34</td>
<td>SBC</td>
<td>1987</td>
<td>Qingjiang River, Hubei Province</td>
</tr>
<tr>
<td>Lizhuxia</td>
<td>Double curvature arch dam</td>
<td>155</td>
<td>2000</td>
<td>16.5</td>
<td>SBC</td>
<td>1988</td>
<td>Yellow River, Qinghai Province</td>
</tr>
<tr>
<td>Tianshengqiao I</td>
<td>Concrete faced rockfill dam</td>
<td>178</td>
<td>1200</td>
<td>102.6</td>
<td>LB</td>
<td>1991</td>
<td>Hongshui River, Guangxi Zhuang Autonomous Region and Guizhou Province</td>
</tr>
<tr>
<td>Ertan</td>
<td>Double curvature arch dam</td>
<td>240</td>
<td>3300</td>
<td>58</td>
<td>SBC</td>
<td>1992</td>
<td>Yalong River, Sichuan Province</td>
</tr>
<tr>
<td>Three Gorges</td>
<td>Gravity dam</td>
<td>185</td>
<td>22500</td>
<td>393</td>
<td>HSB/HPP/SBC</td>
<td>1994</td>
<td>Yangtze River, Hubei Province</td>
</tr>
<tr>
<td>Dachaoshan</td>
<td>RCC gravity dam</td>
<td>115</td>
<td>1350</td>
<td>9.4</td>
<td>HPP</td>
<td>1997</td>
<td>Lancang River, Yunnan Province</td>
</tr>
<tr>
<td>Longtan</td>
<td>RCC gravity dam</td>
<td>216.5</td>
<td>6300</td>
<td>272.7</td>
<td>HPP</td>
<td>2001</td>
<td>Hongshui River, Guangxi Zhuang Autonomous Region</td>
</tr>
<tr>
<td>Xiaowan</td>
<td>Double curvature arch dam</td>
<td>292</td>
<td>4200</td>
<td>150</td>
<td>HPP</td>
<td>2002</td>
<td>Lancang River, Yunnan Province</td>
</tr>
<tr>
<td>Laxiwa</td>
<td>Double curvature arch dam</td>
<td>250</td>
<td>4200</td>
<td>10.56</td>
<td>HPP</td>
<td>2004</td>
<td>Yellow River, Qinghai Province</td>
</tr>
<tr>
<td>Jinping I</td>
<td>Double curvature arch dam</td>
<td>305</td>
<td>3600</td>
<td>77.6</td>
<td>HPP</td>
<td>2005</td>
<td>Yellow River, Sichuan Province</td>
</tr>
<tr>
<td>Xihoudu</td>
<td>Double curvature arch dam</td>
<td>285</td>
<td>12600</td>
<td>126.7</td>
<td>HSB</td>
<td>2005</td>
<td>Jinsha River, Sichuan Province and Yunnan Province</td>
</tr>
<tr>
<td>Xiangjiaba</td>
<td>Gravity dam</td>
<td>162</td>
<td>6400</td>
<td>51.63</td>
<td>HSB</td>
<td>2006</td>
<td>Jinsha River, Sichuan Province and Yunnan Province</td>
</tr>
</tbody>
</table>

Note: LB: layered blasting excavation; HSB: horizontal smooth blasting.

Table 5
Cushion design parameters of typical projects (Pan, 1994; Xu and Lin, 1999; Zhen, 1999).

<table>
<thead>
<tr>
<th>Project</th>
<th>Thickness of PL (m)</th>
<th>Hole diameter (mm)</th>
<th>Cushion length (cm)</th>
<th>Cushion material</th>
<th>Dam area lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ertan</td>
<td>1.0–1.5</td>
<td>38–42</td>
<td>20</td>
<td>Sawdust/rock debris</td>
<td>Syenite/basalt</td>
</tr>
<tr>
<td>Geheyan</td>
<td>1.5–2.0</td>
<td>38–42</td>
<td>20</td>
<td>Sawdust</td>
<td>Flake limestone</td>
</tr>
<tr>
<td>Three Gorges</td>
<td>2.5–3.0</td>
<td>42–76</td>
<td>20–30</td>
<td>Sawdust</td>
<td>Granite</td>
</tr>
</tbody>
</table>

of continuous small-dose blasting, can improve rock-breaking capacity of explosive, and reduce blasting vibration.
Reasonable selection of delay interval, which is generally selected by empirical estimation method in engineering field, has major impacts on blasting effect. The commonly used empirical estimation method in China is pioneered by Zhengyu Zhang from Yangtze River Scientific Research Institute (Zhang, 2003). According to related calculation results and engineering practices, the commonly used delay interval between boreholes often falls into the period of 5–40 ms.

3.1.3. Typical drill-and-blast design
The typical profile of the drill-and-blast design for SBC and its charge structure are shown in Figs. 4 and 5, respectively. The drill-and-blast parameters of SBC at Ertan hydropower station (Pan, 1994) are also listed in Table 6.

3.2. Horizontal smooth blasting
Smooth blasting belongs to controlled contour blasting technology that is widely used in the excavation work of hydropower projects. Recently, horizontal smooth blasting for the PL excavation has been used in many large-scale water resources and hydropower projects, such as Three Gorges Project (Yangtze River, Hubei Province), Xihoudu hydropower station (Jinsha River, Sichuan Province and Yunnan Province), etc., and good results are achieved.

3.2.1. Basic principles
One of the characteristics of explosive detonating in a borehole is that the energy of shock wave is transmitted from the borehole in a very non-discriminating fashion, which means that the shock energy will propagate from the hole to the surrounding rock mass independent of direction. Consequently, the fragmentation of targeted rock mass and the blasting-induced damage of the reserved rock mass will occur.

With intensive drilling on the designed contour line and other relative technical measures, energy will be guided to form the crack between boreholes on the designed contour line in the process of smooth blasting. As a result, the amount and the length of other cracks around the borehole will be reduced observably. Thus, blasting-induced damage of the reserved rock mass will be reduced and a smooth excavation surface will be achieved.

3.2.2. Technical points
(1) Reasonable distance between the spacing and the overburden depth

![Fig. 4. Profile of blasting geometry for SBC.](image)

![Fig. 5. Charge structure of SBC.](image)
Table 6
Drill-and-blast parameters of SBC at Ertna hydropower station (Pan, 1994).

<table>
<thead>
<tr>
<th>Hole depth (m)</th>
<th>Hole diameter (mm)</th>
<th>Spacing (m)</th>
<th>Burden (m)</th>
<th>Cartridge diameter (mm)</th>
<th>Cushion material</th>
<th>Cushion length (m)</th>
<th>Charge per delay (kg)</th>
<th>Charge structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0–2.5</td>
<td>38, 42</td>
<td>0.5–1.0</td>
<td>0.5–1.0</td>
<td>35</td>
<td>Sawdust/rock</td>
<td>0.2</td>
<td>10</td>
<td>Continuous and decoupling</td>
</tr>
</tbody>
</table>

Engineering experience shows that the quality of the foundation surface depends mainly on the relationship between the spacing (S) and the overburden depth (B). Generally, S/B < 0.8 is reasonable, which means that the overburden depth should not be much too small as compared to the spacing.

(2) Detonating at the same time
Cracks growing independently of direction will propagate in a borehole when using explosive detonating. If explosives in the adjacent boreholes are detonated at the same time, a break-through crack between adjacent boreholes will be formed more easily and the amount and the length of other cracks are reduced. It is shown in the experiments by Langefors and Kihlström (1978) that the contour of instantaneous blasting and millisecond delay blasting (less than 100 ms) is superior to that of detonating hole by hole. In practical projects, detonating cord is usually used to reduce the delay of detonating.

(3) Decoupling charge
Decoupling charge is one of the main methods for smooth blasting. By decoupling charge, an optimum charge may be obtained, which is able to form a penetrated crack between adjacent boreholes but not bigger enough to cause unexpected damage to the reserved rock mass. In practical projects, radial decoupling and axial decoupling are achieved by string-shaped charge.

(4) Drilling precision
Drilling quality is another important aspect in smooth blasting. Due to the poor quality of drilling, poor excavation quality incidents sometimes may occur. Both of the deviation of drilling location and drilling angle will affect excavation quality. When the deviation is serious, the contour surface may not be well formed. According to the code DLTS389–2007, in smooth blasting, the deviation of drilling location should be limited in 50 mm, the deviation of drilling angle should be limited in 1°, and unevenness of the excavated surface should be less than 15 cm. Half-cast ratio is also strictly restricted, as shown in Table 7.

3.2.3. Typical drill-and-blast design
The typical profile of the drill-and-blast design for HSB and its charge structure are shown in Figs. 6 and 7, respectively. The drill-and-blast parameters of HSB at Three Gorges Project (Wang, 2003) are also listed in Table 8.

4. Horizontal pre-split of dam foundation without protective layer
Since its first application in the dam foundation excavation of Dongjiang hydropower station (Xiangjiang River, Hunan Province) in 1979, horizontal pre-split of dam foundation without PL has been used in many water resources and hydropower projects, such as diversion tunnel of the Three Gorges Project (Yangtze River, Hubei Province), Jinsuitan hydropower station (Quijiang River, Zhejiang Province), etc.

4.1. Basic principles
The characteristics of pre-split holes are intensively drilled on the designed contour line and decoupling charged. In the process of pre-split blasting, the pre-split charge is firstly detonated to form pre-split crack. The main body of the rock mass is blasting-excavated under the protection of the pre-split cracks, in order to protect the rocks beneath the foundation surface.

The protective effect using the pre-split crack technique on remaining rock mass is mainly reflected in the following two aspects. First, shock wave transited to the remaining rock mass decays because of the reflection of the pre-split crack, so blasting vibration is mitigated. Second, the detonation cracks will be blocked by the pre-split crack and cannot extend to the remaining rock mass.

4.2. Technical points
Both pre-split blasting and smooth blasting are controlled contour blasting techniques that are designed to reduce the BDZ, to control the generation and development of the detonation cracks, and to protect the remaining rock mass and form the excavation

![Fig. 6. Profile of blasting geometry for HSB.](image)

![Fig. 7. Charge structure of HSB.](image)
Table 8

<table>
<thead>
<tr>
<th>Blasting hole type</th>
<th>Hole depth (m)</th>
<th>Hole diameter (mm)</th>
<th>Spacing (m)</th>
<th>Burden (m)</th>
<th>Stemming length (m)</th>
<th>Cartridge diameter (mm)</th>
<th>Unit charge weight (kg·m⁻³)</th>
<th>Linear charge density (g·m⁻¹)</th>
<th>Charge structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production blasting hole</td>
<td>5</td>
<td>46</td>
<td>0.5</td>
<td>1.2</td>
<td>32</td>
<td>0.55</td>
<td></td>
<td></td>
<td>Continuous and decoupling</td>
</tr>
<tr>
<td>Buffer hole</td>
<td>5</td>
<td>46</td>
<td>1.0</td>
<td>1.0</td>
<td>25</td>
<td>0.53</td>
<td></td>
<td></td>
<td>Continuous and decoupling</td>
</tr>
<tr>
<td>Smooth blasting hole</td>
<td>5</td>
<td>46</td>
<td>1.4</td>
<td>1.0</td>
<td>25</td>
<td>180</td>
<td></td>
<td></td>
<td>String-shaped</td>
</tr>
</tbody>
</table>

contour surface. The basic concepts and the main technical points are similar, but the differences are the specific processes and the selection of parameters.

In addition, the excavation of pioneer slot should be conducted firstly in the process of horizontal pre-split blasting for the dam foundation excavation. It is helpful for the improvement of blasting quality, speeding up construction progress for site-specific terrain when excavating the pioneer slot.

4.3. Typical drill-and-blast design

The schematic diagram of the pioneer slot excavation in HPP at Laxiwa hydropower station (Dong et al., 2007) is shown in Fig. 8. The typical profile of the drill-and-blast design for HPP and its charge structure are shown in Figs. 9 and 10, respectively. The drill-and-blast parameters of HPP at the Three Gorges Project (spillway dam section) (Zhen, 2000) are also listed in Table 9.

5. Comparison of different excavation methods of protective layer

The evaluation of rapid construction methods for dam foundation PL mainly includes blasting excavation effect, engineering construction speed, cost, etc. Specially, blasting excavation effect is mainly reflected in damaged zone of the remaining rock mass and the quality of the foundation surface.

Taking Wanan hydropower station (Ganjiang River, Jiangxi Province) and engineering practices in Yantan and Ertan hydropower stations for examples, it can be observed that good blasting excavation effect can be obtained by SBC. For the cases such as Longtan, Laxiwa, Xiangjiaba and Xiluodu hydropower stations, it can be shown that, using contour control blasting technologies, we can get a good excavation contour surface and good blasting effect by both HSB and HPP.

Blasting excavation process can be speeded up by using SBC, but compared to HSB and HPP, quality of the foundation surface is not so good and more subsequent work of foundation surface processing is needed. Good blasting excavation effect can be achieved by HPP, but construction progress is restricted by the excavation of the pioneer slot, and this method is appropriate only when foundation surface area to be excavated is relatively small or terrain condition is relatively good. Comparison between different dam foundation PL excavation methods is shown in Table 10. By using HSB, the excavation quality is guaranteed and the construction progress can be speeded up, thus HSB is suggested as a priority method for dam foundation PL excavation.

6. Problems for protective layer excavation in high in situ stress regions

Most of the large-scale hydropower projects under construction or to be constructed are located in the deep valley regions in Southwest China where high in situ stress is one of the challenges in dam engineering construction. Strong rock unloading and relaxation induced slabling occurred in dam foundation excavation of
Table 9
Drill-and-blast parameters of HPP at the Three Gorges Project (spillway dam section) (Zhen, 2000).

<table>
<thead>
<tr>
<th>Vertical hole</th>
<th>Depth (m)</th>
<th>Diameter (mm)</th>
<th>Spacing (m)</th>
<th>Burden (m)</th>
<th>Stemming length (m)</th>
<th>Cartridge diameter (mm)</th>
<th>Unit charge weight (kg·m⁻¹)</th>
<th>Charge structure</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>76</td>
<td>1.5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>60</td>
<td>0.4</td>
<td>Continuous and decoupling</td>
<td>Bench height is 3 m</td>
</tr>
</tbody>
</table>

Table 10
Comparison between different dam foundation PL excavation methods.

<table>
<thead>
<tr>
<th>Excavation method</th>
<th>Roughness (cm)</th>
<th>BDZ size</th>
<th>Excavation speed</th>
<th>Excavation cost</th>
<th>Comprehensive evaluation</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBC</td>
<td>±25</td>
<td>Big</td>
<td>Slow</td>
<td>More</td>
<td>Foundation surface is not flat and with more joints, so the subsequent foundation surface processing is more good</td>
<td>Good excavation quality, fast construction speed</td>
</tr>
<tr>
<td>HSB</td>
<td>±15</td>
<td>Small</td>
<td>Fast</td>
<td>Less</td>
<td>Good excavation quality, fast construction speed</td>
<td>Good excavation quality, but construction progress is limited by the excavation of the pioneer slot</td>
</tr>
<tr>
<td>HPP</td>
<td>±15</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Xiaowan hydropower station (Liu et al., 2008; Qi et al., 2008; Huang et al., 2010). Typical unloading fissure in the dam foundation excavation of Xiaowan hydropower station is shown in Fig. 11. During the dam foundation excavation at great depth, the high in situ stress is suddenly released and unloading fissures are consequently induced. The unloading fissures are roughly classified into three types, i.e., successive fissures stretching along the initial tectonic fissures, extending extensive fissures controlled by the initial tectonic fissures, and fresh fissures newly born during excavation or after excavation process (Qi et al., 2008; Ma, 2009).

In order to control unloading and relaxation deformation of dam foundation, main techniques in the dam foundation excavation process were used. First, the PL should be reinforced by anchors before blasting excavation. Then, foundation surface should be anchored timely with prestressed anchors before excavation. Finally, dam concrete should be employed immediately when excavation is completed to cover the foundation surface.

7. Conclusions

Foundation PL excavation is an important issue in the construction of hydropower projects in China. The safe operation of the whole project is directly affected by foundation excavation quality, and the construction schedule of the entire project is affected by foundation excavation speed.

The PL excavation often influences the construction schedule. Thus, related dam foundation PL excavation regulations should be strictly reinforced in China. Therefore, in the construction of hydropower projects, the engineering quality should be ensured to improve the construction speed.

At present, researches on the PL excavation are focusing on two issues: on the one hand, how to improve blasting quality and efficiency associated with the construction processes; on the other hand, further exploration on the blasting-induced damage failure criterion and the feasibility of the abolition of PL of dam foundation. At the same time, further research should be also carried out on the problems of dam foundation PL excavation encountered in alpine and gorge regions with high in situ stress.

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