RETRACTED ARTICLE: Blasting excavation and stability control technology for ultra-high steep rock slope of hydropower engineering in China: a review

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ABSTRACT
China has entered a high-speed construction period on hydropower engineering since the late 20th century. Blasting is the major way for rock excavation on large projects, especially for ultra-high steep rock slope. Due to the constraints of topography and geomorphology, requirements on blasting excavation and stability of the reserved rock after blasting are strict for ultra-high steep rock slope. Thus, blasting and reinforcement technology have caused engineer’s attention. This article reviewed the blasting excavation and stability control technology of Chinese hydropower engineering slope and discussed the progress and limitation. Slope on the left bank of Jinping I hydropower station was selected as a case study to reflect the blasting excavation and stability control technology in a rather challenging hydropower engineering slope. The blasting excavation and stability control technology involved in this article can give some reference for other similar engineering projects.

INTRODUCTION
China has the richest hydropower resource around the world. The theory potentiality is 690 million kW and technical exploitation amount is 540 million kW. In recent years, China has entered a high-speed period of construction on large water conservancy and hydropower projects. By the end of 2015, the total installed capacity of hydropower stations has exceeded 300 million kW, which accounted for about 27% of global capacity. Until now, 17 dams whose heights are over 200 m, and more than 200 dams whose heights are between 100 and 200 m have been built successfully. According to geological survey, 66.7% of Chinese hydropower resources are stored in the southwest China. This area is affected by uplift of the Tibetan Plateau (Xu et al. 2014b). Deep narrow valleys and steep slopes make it a suitable place for construction of large hydropower projects. Figure 1 shows some well-known hydropower stations in Southwest China. As the construction scale of hydropower stations becomes large, high engineering slopes are common in actual. For example, excavation heights of slope on Xiaowan hydropower Station and Jinping I hydropower Station are 700 and 530 m, respectively. However, regional tugged topography, complex geological conditions, tectonic activities, high seismic intensity and in-situ stress make construction of high rock slope a challenging work (Wang et al., 2000). Currently, blasting is the main way for rock slope excavation. Blasting effect, such as blasting damage, blasting vibration and blasting loose, is inevitable to occur during engineering slope formation process. Thus, stability of high steep rock slope has been one of the key technical problems on hydropower projects construction.

Scientific and accurate design is a basis for hydropower station. There was a period when blasting excavation is almost dependent on experience. After years of engineering practice, blasting excavation technology developed from small scale and low efficiency to large scale and fast construction. In the last century, concentrated charge cavern blasting was used in engineering. Then strip charge cavern blasting and springing blasting were the main blasting techniques in 1960s and in 1970s (Liu, 2007). Small bench blasting was gradually replaced by deep-hole bench blasting to improve the efficiency. Later, contour blasting has been successfully used in Gezhouba hydropower station. At present, combination of deep-hole bench blasting and contour blasting is the common blasting method. Due to the complicated geological environment, blasting excavation technology develops constantly. Hustrulid and Lu (2002) improved the Holmberg-Persson method into blasting excavation and applied it on the Three Gorges project successfully. Fu et al. (2004) developed the hole-by-hole detonation vibration deduction technology of deep-hole bench blasting. The peak of blasting vibration was reduced significantly and main frequency was...
improved. Zhang et al. (2013) proposed the superposed simulated prediction model based on vibration wave of single-hole blasting. It can predict peak of blasting vibration velocity as well as the completed vibration waveform. J. Liu et al. (2014) proposed a method, which can automatically complete the whole bench blast design according to blast area configuration and several parameters. For the goal of low consumption and slight damage, Chen et al. (2016b) applied the wide-space and air-decking pre-splitting blasting technique into Xiangjiaba project and got a good result.

After blasting, stability of reserved rock will reduce. In order to minimize the adverse effects of blasting, reinforcement measure was applied. At the early time, some rock mass were simply cut away to control the sliding force and retaining wall was applied to make the slope keep balance by gravity. Obviously, previous reinforcements were not designed under precise calculation and structural analysis. With the development of modern supporting theory, which is based on classical theory of pressure, medium pressure theory proposed by Terzaghi et al. (1996) and New Austrian Tunnelling Method (Rabcewicz, 2008), reinforcement technique update constantly. Panek (1956) put forward the suspension effect theory, which thought anchor is to make weak, loose and unstable rock hang on the deep stable rock to restrain rock sliding by abscission layer. Based on it, composite beam effect theory was proposed. The lamellar rock was thought as a kind of beam and the anchor fasten them to composite beams. Layers squeezed with each other and friction was increased while internal stress and deflection was reduced greatly. However, for the extremely poor geology, ordinary measurements may not ensure the stability of slope and optimization design is put forward. Song et al. (2011b) combined shearing-resistance tunnel, anchor cavern and inclined shaft for a comprehensive treatment on large-scale rock slope. Yang and Huang (2006) developed analysis database of reinforcement for an efficient and simple way to design the supporting structures. Also, slope bioengineering (Zhou & Zhang, 2003) has been a hotspot with focus on environmental awareness.

During blasting and reinforcement process, slope stability is the key point. There are many stability control methods, such as static limit equilibrium to quasi-static limit equilibrium based on natural earthquake (Sarma, 1981), dynamic finite element method, discrete element method (DEM), infinite boundary element method, etc. The limit equilibrium method (Gurocak et al., 2008; Ling & Cheng, 1997) can judge the security of slope intuitively based on safety factor; Toki and Miura (1985) applied the numerical model to solve safety factor based on dynamic finite element method; Cundall (1987) proposed DEM to solve the large deformation and instability of slope based on rock discontinuity. Bhasin and Kaynia (2004) used DEM that contains Barton-Bandis non-linear joint shear strength criterion (Barton, 1990) on the stability analysis of a 700 m-high rock slope in western Norway. Shi and Goodman (1985), Hatzor et al. (2004), and J. Wu et al. (2005) used discontinuous deformation analysis (DDA) to study dynamic stability of jointed rock slope. J. H. Zhang et al. (2001) applied rigid body-spring element method (RBSM) to static and dynamic stability on slope foundation. Q. Yang et al. (2008) proposed deformation reinforced...
theory to evaluate global stability based on complementary energy norm and proposed reinforcement measure based on unbalanced force. Bui et al. (2011) presented an extension of the smoothed particle hydrodynamics (SPH) method to evaluate the slope stability. Lin et al. (2016) put forward a new toppling failure mode to explain the large deformation in a high steep slope based on a fluid-solid coupling model.

As above, technology of blasting and reinforcement has been on continuous development. With the geological conditions going on complicated, construction method should be optimized timely. This article analyzed blasting excavation and stability control technique of Chinese ultra-high steep rock slope on hydropower engineering in recent years. A case study about slope on the left bank of Jinping I hydropower station is studied to show current project construction status. Summary and discussion in this article can give reference and future direction for ultra-high steep rock slope.

Design principle and safety criterion of ultra-high steep rock slope

According to Chinese <Specification of excavation blasting for hydropower and water resources projects (DL/T5135-2013)>, high steep slope is defined as the slope taller than 50 m, and steeper than 55°. <Design specification for slope of hydropower and water conservancy project (DL/T5353-2006) > classifies slope by height. The height larger than 300 m called ultra-high slope, 100–300 m called super high slope and 30–100 m called high slope. There is no uniform definition for ultra-high slope because it is uncommon in other projects except hydropower projects. However, there is no doubt that demands on excavation design and stability control will be stricter as the slope becomes higher and steeper.

During the process of blasting excavation and reinforcement, the prime difficulties are as follows: (1) complex geological conditions, severe-weathered rock mass and transient unloading release may lead to geological hazards easily. (2) the effect of blasting vibration on slope and nearby buildings is indispensable. (3) construction site is so stenosis that a variety of workstages could not get on work at the same time due to the deep narrow valleys and precipitous terrain, which makes construction organization and arrangement more difficult. (4) tumble of broken stone may raise the river level up and set up barriers for latter closure. (5) rock loose and deformation caused by transient unloading is marked especially under high in-situ stress environment. And physical, mechanical and hydraulic properties of rock are greatly changed (Malmgren et al., 2007). Based on above, there are great challenges on the construction of ultra-high steep rock slope for engineer to achieve. Design principle and stability criterion of slope are essential to subsequent construction.

Design principle of slope

According to <Design specification for slope of hydropower and water conservancy project (DL/T5353-2006)>, <Design code for engineered slopes in water resources and hydropower projects (SL386-2007)>, and construction characteristics of excavation and reinforcement, the design principles for ultra-high steep rock slope are as follows: (1) rock stability and risk assessment should be fully analyzed in architectural design. (2) geological analysis should be systematic and comprehensive, especially the deep accumulated body, big fault, structural plane along the slope and high in-situ stress. (3) blasting excavation plan should be reasonable to meet the demand that excavating less and using advanced reinforcement. Strong unloading caused by excavation should be in the first consideration. (4) design parameters, such as slope pattern, bench width, height and gradient of bench, should be determined based on geological prospecting and construction environment. Generally, the width of bench is no less than 2 m and the height is no more than 30 m. Blasting scale, blasting technology and construction sequence should be in proper arrangement. (3) measures that can improve stability by the rock itself should be in the first consideration and reinforcement is the second alternative when stability and deformation of the natural slope could not meet the construction requirement. (4) reinforcement plan should be optimized according to construction plan, schedule, cost and treatment effect. Effective measures must be taken when failure occurs even the project is completed. (5) rock in different depth can be classified as surface, superficial and deep. Designer should analyze the rock stability and take targeted reinforcement for different part, respectively.

Stability criterion of slope

During the process of blasting excavation of slope, transient unloading makes stress and displacement readjust. Frequent blasting vibration makes original rock fissures and beddings expand or dislocate. These adverse effects may lead to instability or safety accidents. Thus, blasting plan should be designed based on stability criterion to avoid possible instability problems.

Static criterion

In static criterion, different criterion index, such as stress, displacement and safety factor, can be applied for different failure modes. After blasting, unloading makes stress field redistribute, which results in stress concentration or relaxation (Wu et al., 2009). Stress criterion is to judge stable state according to stress change by rock strength criterions. Displacement is the most intuitive reflection on rock deformation or slippage and it is easy to get, such as marking monitor in the faults (Newcomen & Dick,
Displacement criterion is mainly judged by maximum displacement limit range and residual deformation increase rate. Displacement-velocity criterion has often been applied in slope engineering.

The factor of safety $F$ is an important criterion on slope stability. It is traditionally defined as the ratio of actual soil shear strength to minimum shear strength required to prevent failure (Bishop, 1955; Dawson et al., 2015). As Duncan (1996) points out, $F$ is the factor by which the soil shear strength must be divided to bring the slope to the verge of failure. Since it is defined as a shear strength reduction factor, an obvious way of computing $F$ with a finite element or finite difference program is simply to reduce the soil shear strength until collapse occurs.

**Dynamic criterion**

After blasting, strong dynamic response is generated in the reserved rock. Mechanical properties of structural plane reduced and creep process of sliding mass is accelerated. Structural body may slide along advantage occurrence and landslides occur. Under strong blasting load, static criterion is unsuitable to ensure slope stability and dynamic stability becomes more important.

Dynamic criterion is mainly summarized from engineering experience since dynamic load mechanism has not been analyzed clearly enough. The main dynamic factor is blasting vibration (Lu et al., 2012b). Lots of experimental results show that vibration has a close relationship with peak particle velocity (PPV) (Nguyen et al., 2019a, 2019b) which can be seen as the most direct reflection of dynamic response. PPV of slope toe is the common monitored data and PPV of the slope top is also necessary to prevent blasting vibration amplification for high steep slope. Recently, blasting vibration frequency and peak particle vibration acceleration are also used to judge dynamic damage caused by blasting excavation. According to Chinese <Safety regulations for blasting > (GB6722-2014), combined criteria of PPV and vibration frequency is recommended. The seismic wave frequency band is divided into several segments and allowable vibration velocity is set up for each range. For blasting excavation of slope, allowable blasting vibration velocities are between 8 and 15 cm/s. If the frequency is high, the values should be lower.

**Excavation method of slope**

Bench blasting without contour borehole was the original blasting technique and then engineer began to focus on the importance of contour borehole. However, large blasting vibration and severe damage to the reserved slope were the troubles. At present, digital electronic detonator is applied in slope engineering to control the effect of blasting vibration. Excavation methods of slope are mainly deep-hole blasting, presplitting blasting, smooth blasting or their combination. Deep-hole bench blasting (Zhang...
et al., 2003) generally refers to multilevel bench blasting whose charge pore is greater than 50 mm and hole depth is greater than 5 m. It is the main method in Chinese hydropower engineering slope for its large blasting square amount, great crushing effect and low vibration. Figure 4 shows blasting design of slope on the left bank of Jinping I hydropower station. Presplitting blasting was applied for the slope rock excavation. It is a contour blasting technology, which plays dense holes (I1) with small explosives along contour line to blast a fissure first. It is to prevent reserved rock damage caused by main boreholes. And then main boreholes (I7→I6→I5→I4→I3) and buffer hole (I2) detonate in sequence. Smooth blasting is to arrange holes densely with small explosive along final excavation line. And smooth holes (I1) detonate after main boreholes (I7→I6→I5→I4→I3) and buffer hole (I2). Compared with presplitting blasting, little damage was caused on the reserved rock by smooth blasting. However, repeated dynamic damage can not be shield. Applicable scope of the two methods are different. Thus, proper choice should be made based on geological conditions or engineering demand.

In actual project, blasting method is optimized to control the negative blasting effects. During blasting excavation of shiplock slope in the Three Gorges project, presplit blasting with lateral free face has been successfully used to slope excavation near the contour (Hu et al., 2014). Figure 4 shows the optimization-blasting diagram. It combines the advantages of traditional presplitting blasting and smooth blasting. The main boreholes that far from the designed contour (I7→I6→I5) detonate first. The first detonated boreholes break a mass of rock and provide a closer lateral free face. Then presplitting hole (I1), main boreholes near the contour (I4-I3), and buffer hole (I2) detonate in turn. After presplitting blasting, energy transfers to the awaited explosive rock so that energy for reserved rock reduced. In the meantime, clamping action of the rock is weakened. Formation of pre-splitting cracks speed up and detonation gases discharge quickly.

**Effect of in situ stress on blasting excavation**

Geological prospecting indicates that high in situ stress is a usual phenomenon in Southwest China, which is formed by cutting valley rapidly. Strong and frequent geotectonic movement caused four stress zones on slope: stress reducing zone, stress increasing zone, original stress zone and high stress zone. High stress zone exists at the bottom of riverbed and stress value is often higher than that of stress increasing zone on the bank slope. Sudden release of high in-situ stress makes instantaneous unloading of rock rather high and causes internal stress redistribution and concentration near the free surface.

During the blasting excavation in permanent shiplock of the Three Gorges project, sudden release of high in-situ stress caused strong rock deformation. Researchers studied this phenomenon and found that blasting load transfer vast energy into rock. Intense...
release of those energy stored in the rock lead to internal stress redistribution and then local stress concentration appeared. During the unloading process, tensile or shear failure are easy to form subject to the circulation of stress concentration and relaxation. In the meantime, vibration induced by in-situ stress unloading may exceed the blasting load and blasting loose zone or damage range become larger (Lu et al., 2012a). Thus, in terms of the special high in situ stress, blasting design must consider rock failure mechanism as much as possible and some special measures must be taken on the quite weaken rock. Reasonable resistance line and procedure optimization can help control the unloading direction or limit excavation load. Also, shallow-hole blasting or reducing the single explosive charge can help control unloading loose.

**Stability control technique of ultra-high steep rock slope**

**Reinforcement technique of slope**

Under blasting vibration, fissures, beddings and fractures are easy to occur and expand. Physical characteristics of reserved rock mass are reduced. Stability and safety of the project and relative buildings are difficult to ensure without scientific and rational reinforcement measures.

Reinforcement measures are often used in high slope engineering with complicated geological conditions (L. Zhang et al., 2015). Anchored structures, anti-slip support, slope flexible support and grouting engineering are the common used reinforcement methods. The anchored structure components comprise (pre-stressed) anchor, pre-stressed cable, soil nailing wall, bolt-shotcrete support and etc. Anti-slip support components include anti-sliding wall (such as reinforced retaining wall, anchor slab retaining wall, pre-stressed anchor retaining wall, anchor retaining wall) and anti-slide pile (anti-slide single pile, frame assembled anti-slide pile, bearing platform anti-slide pile, anti-slide steel frame pile, steel pipe pile, sheet-pile, anti-slide pile, anchor pile). Passive flexible structure mainly consists of wire rope net, steel columns, support rope, tension anchored rope, decompression ring, etc. Grouting is a method that strengthens the jointed rock by injecting grout into gaps inside the rock. It is mainly applied in the slope engineering where large faults exist.

Bolt and anchor cable are the most frequently used measures. Bolt is used for seriously weathered slope with mature joint fissure. It consolidates weaken rock together by friction force between each other. Anchor makes the weak, loose and unstable rock suspend in stable rock to prevent slipping separation. Currently, free single-hole multi anchorage antisepic pre-stressed cable is often used in slope engineering. Furthermore, if the rock is fast weathered, shallow sliding, creeping or difficult to clean, it is time to apply active flexible protective measures. The continuous support surface protected system is formed of bolts and supporting ropes to make the metal net cover the slope tightly.

In recent years, conventional reinforcement cannot live up to the expectations with extremely complex condition. New types of reinforcement measure, such as shearing-resistance tunnel and anchor cavern, are proposed. Shearing-resistance tunnel is a kind of horizontal strip hole arranged along the sliding face and filled with concrete. Its most prominent mechanism is “replacement”. Anchor cavern refers to the horizontal hole across sliding surface along with the direction of sliding. It is also filled with concrete. Figure 5 shows shearing-resistance tunnel applied in the slope on the left bank of Jinping I. The tunnel is mainly set on the jointed rock area, which consists of lamprophyre veins and f13-9. It will limit further deformation and avoid slope slumping.

When the internal joint cracks are extremely developed or various types of faults, dykes, sliding surface are quite deep, comprehensive reinforcement method is applied. Builders attempt to combine several rock replacement structures with traditional support for integrated treatment. As shown in Figure 6, Song et al. (2011) arranged shearing-resistance tunnels alternately along sliding plane in compression-shear zone and put anchor caverns perpendicular to sliding surface cross the shearing-resistance tunnels. Replaceable inclined shafts connect upper and lower shearing-resistance into integration to replace weak rock on sliding plane. This comprehensive management takes full advantage of various support structures and is beneficial to global and local stability.

**Control technique of blasting effect**

After blasting, reserved rock mass may get damaged and stability of the slope is difficult to ensure. Blasting damage and blasting loose are easily to appear on the near field of blast source and blasting vibration is the main effect on the far field. Thus, some measures should be applied due to these negative blasting effects.

**Blasting vibration control**

The influences of blasting vibration on high rock slope are mainly two aspects: on the one hand, frequent vibration loads result in the decrease on anti-shear strength of structural plane; on the other hand, inertia force makes the whole downhill strength increase and may lead to dynamic instability (Liu, 2007). In practice, measures that can reduce blasting vibration are often taken from explosion source and transmission route of blast stress wave. For explosion source, it includes using
millisecond detonating technology, limiting the maximum amount of explosive charge per delay, choosing proper blast-hole diameter, using decouple charge structure, adding buffer holes, choosing correct millisecond delay interval and etc. For transmission route, applying presplitting blasting, excavating damping ditch, arranging the resistance line direction properly or others can be taken into consideration (SL386-2007). Meanwhile, controlling the blasting operation scale and reducing the excavation boundary dimension for every blast are effective means to prevent vibrational hazard (J. Yang et al., 2016).

**Blasting damage control**

Rock is a kind of brittle material whose compressive strength is much higher than tensile strength. Under strong impact stress wave, compressive damage generates around the borehole wall firstly. Then, tensile and shear damage come into being with stress wave propagation. At last, damage evolve into cracks and intact rock get various extent destroyed. Thus, blasting damage control can be started with decreasing peak blasting pressure of the borehole wall. Large coefficient of decoupling charge, appropriate explosive type, low single blasting charge or maximum single blow explosive charge and proper delay time are the ordinary measures to avoid superposition of blasting load.

In order to minimize dynamic damage on the reserved rock, presplitting blasting or smooth blasting is applied on the designed contour excavation. Different order of them shows different dynamic damage on reserved rock. The presplitting blasting generates severe but small damage zone while the smooth blasting produce slightly severe but large zone. Any single way may not get good results when the contour quality is on strict demand. In order to utilize advantages of the two methods, presplitting blasting with lateral free face is developed. Damage

![Figure 5. Design scheme of shearing-resistance tunnel of slope on the left bank of Jinping I hydropower station (revised from Song et al., 2011b). (a) Arrangement of shearing-resistance tunnel (b) Design scheme of shearing-resistance tunnel section.](image)

![Figure 6. New concrete shearing structures for slope reinforcement (Song et al., 2011b) (a) Profile (b) Elevation drawing.](image)

1-Designed contour, 2-Prestressed anchor, 3-Shearing-resistance tunnel, 4-Anchor cavern, 5-Replaceable inclined shafts, 6-Longitudinal drainage tunnel, 7-Drainage hole, 8-Sliding plane, 9-Dike, 10-Unloading crack.
extent is greatly reduced with shorter lateral resistance line. It not only gives full play of isolation function of presplitting blasting, but also limits dynamic damage on the rock in a way.

Similarly, optimization on smooth blasting can decrease cumulative damage, especially damage on the reserved rock deriving from main borehole and buffer hole. As shown in Figure 7, two changes have been taken. One is to adjust distance between the last main hole and contour face. The other is to add cautious blasting area between the last main borehole and contour face. If conditions permit, weak buffer blasting can be designed followed by small perturbations principle. The charge of buffer hole can gradually reduce with distance from the contour face decreasing.

**Blasting loose control**

Blasting load dominate accumulation of rock energy by means of extrusion process, and result in displacement and loose with stored energy releasing instantly. The quicker the unloading rate, the larger the loose displacement. And uninstall tensile wave generated by transient unloading of in situ stress may also result in rock loose (Chen et al., 2016b). Manifestation of blasting loose is shear dislocation in vertical and open of weak structural surface in parallel.

The main factors that affect loose displacement of dynamic unloading are the size of excavation step and the rate of dynamic unloading. In blasting network design, reasonable delayed interval of rowing space and hole space, or charging structure optimization can reduce the peak load and unloading rate. In that case, open and loose of the structural plane can be controlled. Moreover, length and direction of resistance line are closely relative to maximum unloading stress. Resistance line with smaller length or approximately perpendicular to loose direction is more favorable to prevent greater dynamic unloading loose.

**Figure 8** is partial excavation layout of a certain slope. There are two excavation plans. One is to put free surface on the left side (direction 1). The other is on the valley side (direction 2). If direction 2 is applied, reserved rock locates on the backward of blasting area. Unloading direction is consistent with loose displacement, and displacement is the maximum in this way. If direction 1 is applied, reserved rock locates on the side. Unloading direction is vertical with the loose displacement. In this case, the loose effect can be reduced.

**Safety monitoring technique of slope**

During construction and operation of ultra-high steep rock slope, informational monitoring on stability is necessary. Principles for blasting safety monitor are as follow (Zhang et al., 2003): (1) security monitor on blasting vibration should throughout entire construction period and feedback analysis should be timely. (2) data collected from dynamic and static monitor, key and general monitor, overall and local monitor should be in...
contrastive analysis (Cawood, 2006). (3) reliable, stable, high precision and simple fast instruments and methods are the prior choice. Multiple methods and apparatus should be adopted to monitor the same variable for the key part and results need to be verified mutually. (4) sites and times of monitoring should meet blasting safety requirements to guarantee achievement data completed and reliable. (5) construction environment or other outside factors like weather conditions also need to be considered.

Different projects need different monitor instruments. Velocimeter, accelerometer and dynamic strain gauge are used to get the motion and dynamic parameters of the rock. Peak particle vibration velocity is the main monitored parameter, which is a reflection about dynamic response after blasting. Likewise, borehole inclinometer and multi-point extensometer are used to monitor displacement change. Integration of collected data can analyze the stable state and slip trend. As for the stress monitor, it often uses the pressure cell, anchor dynamometer and etc.

Optimization on blasting excavation and reinforcement of slope

Optimization technology of blasting and reinforcement has been discussed in Sections 3 and 4. In order to reduce mutual interference between blasting excavation and reinforcement, optimization on construction procedure is also necessary. Generally, the optimized principles is guided by the following: (1) temporary or random support structures, such as random bolt, anchor, first sprayed concrete and locked anchor bar of the last bench, should be applied timely. (2) blasting excavation that carried out after reinforcement can minimize rock deformation compared with blasting before reinforcement, especially for easily instable rock (Zhang et al., 2003). (3) for the potential sliding rock which is meet the stable demands after anchor, timely reinforcement and drainage during the construction are essential. (4) pre-excavation of the drainage tunnels and anchor caverns is beneficial to drainage, reduce groundwater level, and enhance slope stability. For the slope, which is conducted with anchor caverns, shearing-resistance tunnels or drainage tunnels, excavation of these holes should be ahead of the slope excavation. Followed by the above principles, stability of slope can be ensured during construction period.

Case Study - Excavation and reinforcement of slope on the left bank of Jinping I hydropower station

General situation of Jinping I hydropower station

Jinping I hydropower station, located in a deep valley of the Yalong River, is the first of five hydropower stations to be constructed in middle and low reaches of the river (Huang et al., 2010). Figure 9 shows the general condition of Jinping I hydropower station.

The dam is 305 m high, which is the world’s highest double-curvature arch dam until now. The retained...
reservoir level is EL.1880 m and storage capacity is 7.765 billion m$^3$. Total installed capacity is 3600 MW.

Geological cross-section of slope on the left bank is shown in Figure 10. The excavated height was 530 m and excavation area reached up to 5.5 million m$^3$. The left abutment formed a scarp slope with alternating weaken and strong rock. Deep fractures in groups, commonly known as “Jinping deep crack”, were found within the superficial unloading belt and it is definitely a threat to the left slope stability. It was a special geological phenomenon that consists of fault $f_5$, $f_8$, $f_{42-9}$, lamprophyre veins X and fissure SL$_{44-1}$. The main strike direction was NE. Advantage dip was between N50° and 90°E. Fault $f_5$, $f_8$ and lamprophyre X were relatively long and wide with poor property. $F_5$ was a strike-slip thrust fault of 1.8 km long. $F_8$ was about 1.4 km long with a relative small thickness of crushed zone and crossed with $f_5$ in the middle part of the slope. SL$_{44-1}$ was a deep tensile crack at the upstream boundary. $F_{42-9}$ was at the downstream boundary with lamprophyre X as the internal sliding face. These faults may produce a wedge failure mode that controlled the slope deformation. Under particular high in-situ stress environment and lithologic conditions, stress released intensely accompanied with valley cutting. The deep unloading fissure system was formed on the basis of unloading rifting on original structures (S. Qi et al., 2004). Due to the above, the geological conditions are so complex that it is a challenge on slope excavation. Thus, the left slope of Jinping I can be called the largest scale but worst stable slope among Chinese hydropower stations.

**Blasting excavation and reinforcement**

The main design principles of blasting excavation and reinforcement were “less excavation, weak blasting, strong support, hierarchical partitioning support, overall control, cover surface with points” (Song et al., 2011). The procedures were hierarchical excavation from top to down and excavation with simultaneous reinforcement. Figure 2 shows the diagram of layering and zoning of the excavated area. The area was mainly divided into three zones and each block applied blasting operation from outside to inside. In order to ensure the integrity of bedrock and surface smoothness after excavation, presplitting blasting was applied. Blasthole arrangement is shown in Figure 11 and blasting parameters are shown in Table 1. Relative blasting parameters were set strictly according to specifications and field test. For the part that was not suitable to apply presplitting blasting, protective layer was reserved and single-row drilling blasting method was used.

According to fundamental topographic and geological conditions, overall stability was set as the control mode and targeted reinforcement was designed for sub-surface, shallow surface and deep surface respectively (Song et al., 2011; Li et al., 2007). Pre-consolidated grouting was implemented firstly by
arranging pre-consolidated grouting holes between two berms to improve slope integrity and avoid rock relaxation or slide after blasting. For deep rock stability, pre-stress anchor cable and shearing-resistance tunnel were the main reinforcement measurements. For the superficial rock, reinforcement was concrete framed beam, shotcrete, anchor, anchor beam and pre-stress anchor. For the part out of slope opening line 8–15 m, shotcrete with wire mesh, anchor and flexible passive protected network were the prime measures after covering layer was cleaned away. In the meantime, anti-seepage and drainage system were set to reduce potential rock mass failure due to seepage. For the dangerous rock body outside the opening line, anti-seepage and drainage system were set to reduce potential rock mass failure due to seepage. For the dangerous rock body outside the opening line, partly clear-away, bolt, anchor or active protected network support was applied due to the actual engineering geological conditions. Above reinforcement plans have obtained desired effect. The slope deformation has settled to negligible amounts with no further significant degree.

As for the special Jinping deep crack, concrete shearing structure and anchoring system were adopted. As shown in Figure 5, there were three shearing-resistance tunnels in the EL.1883, 1860 and 1834 m arranged along fault $f_{42.9}$ to replace the bottom slip surface of tensile cleft body. Configuration of steel bar has been set to further increase the anti-shearing strength. Contact grouting was used to strengthen replaced concrete and rock interface. Consolidation grouting was to improve stability of the faults on crushing zone. Deformation of lamprophyre veins X was chiefly caused by dislocation of $f_{42.9}$. Thus, reinforcement of $f_{42.9}$ can inhibit deformation of lamprophyre veins X in a way. System anchor was employed on the fractured zone and shallow-buried section of faults. This comprehensive treatment program enhanced overall stability, and ensured slope safety in construction and operation successfully.

**Stability control and safety monitor**

According to the report compiled by Chengdu Engineering Corporation Limited of PowerChina, the rock above EL.1885 m were broken sand slate that was easy to occur partial sliding and toppling failure. During blasting excavation, undesirable structural planes, such as $f_{42.9}$, $f_5$, exposed gradually and stability of reserved rock was decreased. The stability of slopes was analyzed by the limit equilibrium analysis, which provided a direct measure of stability in terms of the safety factor (Kentli & Topal, 2004). Under normal circumstances, safety factor of natural slope remained at 1.0. After blasting excavation, safety factors changed from 1.13 to 0.99 with the different occurrence simulation on SL44-1. Safety of factor was calculated by limit equilibrium method or finite-element-based strength reduction method. The finite element strength reduction method was used for overall stability. It was among 1.75–1.70 on natural condition, 1.67–1.40 when excavating to EL.1885 m, and 1.05–0.95 after excavation completed.

It is noted that stability of the slope was decreased after blasting excavation. Thus, reinforcement plan was indispensable. In the designed stage of
reinforcement plan, engineers have studied stability of the slope by kinds of experimental and numerical methods and put forward possible failure may occur. Relative researches are shown in Table 2. Operating conditions were mainly aimed at potential sliding part of \( f_0, f_0, S_{L44-1} \) and lamprophyre veins \( X \). Dynamic finite element method (Y. Liu et al., 2013; Xu et al., 2011) was used on numerical simulation of blasting excavation process of the left slope to analyze global and local stability. The effect of blasting vibration on pre-stressed anchor on the upper part was evaluated. And some critical advices were also proposed to optimize the construction program.

Thorough monitoring system, which includes appearance, inward vision, stress, deformation, special structures border and reinforcement, has been established to ensure slope safety under continuous excavation (Xu et al., 2014a). Eighty external observation piers were set up on three divided monitoring areas to arrange monitoring instruments objectively. In allusion to deep cracks, deformation detectors, such as graphite rod meter, were put in the exploratory adit and drainage tunnel for deep deformation monitor. Furthermore, PPV was monitored after every blasting excavation and the harmful effects were evaluated timely.

Thanks to the above, Jinping I hydropower station, which has the most difficult slope on excavation and reinforcement, can be built successfully.

**Conclusions**

With the construction of many hydropower stations in China, unprecedented challenges make blasting excavation and stability control of ultra-high steep rock slope innovate continuously. Main works and conclusions of this article are summarized as follows:

(1) A series of design principles and stability criterion of ultra-high steep rock slope was summed up. Stability analyze mainly includes static and dynamic analysis. Safety factor of static criterion and PPV combining with dominant vibration frequency of dynamic criterion are the two most frequently used index in practice.

(2) Blasting excavation procedures are generally excavation from top to down and reasonable layer and zone division. Proper arrangement, such as reinforcement before excavation, reinforcement and excavation at the same time, can reduce adverse blasting effects. Moreover, presplitting blasting with lateral free face or optimized smooth blasting can be selected to reduce damage on reserved rock and control blasting vibration. And high in situ stress in southwest China should not be neglected. Combination of presplitting and smooth blasting or procedure optimization can be applied to control the effect of in-situ stress to some extent.

(3) Conventional reinforcement measures, such as bolt, anchor, anti-slide pile, just can solve part of stability problems. When it comes to the complex geological conditions, new technology, such as anchor cavern, shearing-resistance tunnel, may be better choice for large-scale slope engineering. Blasting damage and blasting loose are easy to occur on the near-field of blast source, and blasting vibration is generated on the far field. In practice, blasting parameters optimization, scale

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**Table 2. Summary on stability analysis of slope on the left bank of Jinping I hydropower station.**

| No. | Author                  | Method                                      | Criteria                  | Conclusion                                      |
|-----|-------------------------|---------------------------------------------|---------------------------|-------------------------------------------------|
| 1   | Li et al. (2007)        | FINAL                                       | safety factor             | Four conditions are set and conclude that the safety factor will increase after the pre-stressed anchor cable. Overloading, strength decreasing are applied to simulate different condition and conclude that the reinforcement treatment is necessary. |
| 2   | Fei et al. (2010)       | Geo-mechanical model testing with temperature-analogue material | safety factor             |                                                  |
| 3   | S. W. Qi et al. (2010) | FLAC3D with Sarnia limited equilibrium approach, Griffith and Lane’s strength reduction method | safety factor             | Some remedial works are beneficial to improve stability. |
| 4   | Q. Y. Chen et al. (2011)| ANSYS/LS-DYNA                               | safety factor, PPV         | Fault f5 and f8 will influence the blasting excavation of 1910 m-1885 m. |
| 5   | Xu et al. (2011b)       | RFPA-SRM                                    | safety factor             | The slope is subject to brittle tensile fracturing subparallel to the maximum principal stress. |
| 6   | Z. F. Qi et al. (2012)  | ANSYS with finite element-based             | safety factor             | Put forward a new criterion to calculate safety factor. And it will get increasing after the three shearing-resistance tunnels. |
| 7   | Y. Liu et al. (2013)    | Multi-grid method                           | safety factor             | The safety factor decreased with the excavation going on, some measures should be taken to ensure stability. |
| 8   | Xu et al. (2014a)       | RFPA3D–centrifugal model considering microseismic damage | damage vibration          | Microseismic activity induced by construction disturbance only slightly affects the stability of the slope. |
| 9   | Y. Chen et al. (2015)   | 3D geomechanical model test by              | Overloading, multiple     | The treatment measures combining with concrete cushion, concrete replacement grids and slot-cutting replacement are feasible to improve the stability. |
| 10  | Lin et al. (2015)       | Large-scale rotating 3D                     | safety factor             | Reinforcement installed in the weak rock can improve the anti-slide safety factor of the slope. |
control, proper arrangement on resistant line, contour blasting or other control measures are applied to restrain the harmful effects.

Continuous development of blasting excavation and stability control technology guarantees hydropower stations in a safe state. However, there are still many stability problems need to be further studied. The complexity of rock can not be estimated adequately and the designed plan of blasting excavation and reinforcement should be adjusted during slope construction. Detailed geological prospecting technology need to be further analyzed. Moreover, high in situ stress is an important factor in southwest China. Transient unloading phenomenon induced by it needs further detailed study. New control method of dynamic loose can be proposed by learning the coupling effect of blasting and transient unloading during the dynamic excavation process.

Disclosure statement

On behalf of all authors, I hereby attest that there is no conflict of interest regarding financial relationships, intellectual property, or any point mentioned under the publishing ethics.

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