Design method of high slope engineering for hydroelectric power in China based on slope structure characteristics

Song Shengwu, Feng Xumin*, Xiao Pingxi, Li Xiaolong

PowerChina Chengdu Engineering Corporation Limited, Chengdu, 610072, China
*Corresponding author e-mail: 2006074@chidi.com.cn

Abstract. This paper briefly describes the particularity and design difficulty of hydropower engineering slopes and general situation of hydropower engineering slope design in China. According to the stability property, a slope structure system is established. A systematic design method for high slope engineering based on slope structure characteristics and Chinese engineering experience is proposed; that is, a design process with four stages and 11 steps. Additionally, the research tasks and methods of each design stage and the research content of each step are introduced. It is believed that identifying and determining the slope structure type in the engineering area is a key step in the slope design process, and the key objects of the design are the poorly stable Class III and Class IV slopes and unstable Class V slopes. The design method has a complete system structure, detailed and specific content, and strong operability and guidance.

Keywords: high slope, slope structure, design process, hydropower engineering.

1. Introduction

People have been studying the deformation and failure of slopes since the beginning of engineering practices. In the first half of the 20th century, a limit equilibrium analysis method focusing on the failure mechanism of landslide or soil slope was gradually formed and improved. In the second half of the 20th century, the rapid development of rock mechanics and numerical analysis methods provided a theoretical basis for slope design [1]. In 1973, the book "Rock Slope Engineering" edited by E. Hoek and J.W Bray, was published, and the system design method based on mining engineering slope was first proposed [2]. A hydropower slope project, especially the slope of a "high dam and large reservoir", is vulnerable to the influence of reservoir impoundment, reservoir water level fluctuation, dam flood discharge erosion, and atomization precipitation. During the operation of a project, instability and damage often occur, affecting the normal safe operation of the project and even causing engineering disasters or huge social disasters, such as the landslide of the Vajont Reservoir in Italy in 1963. Thus, slope design is difficult. To make rational use of clean and renewable water resources, China, like other countries in the world, has built many high dam and large reservoir power stations in recent decades. According to incomplete statistics, more than 190 high dams over 100 m tall have been designed and built in China, of which there are more than 20 high dams over 200 m tall, and the maximum dam height is 305 m [3]. There are 137 reservoirs with more than 1 billion cubic meters of volume, including 16 reservoirs with more than 10 billion cubic meters of volume, and the largest reservoir has a volume of 39.3 billion cubic meters. Additionally, many high slopes with rarely seen in the world have been designed. According to the preliminary statistics, there are 22 super-high slopes over 300
m tall in the hub area. Among them, there are four slopes with heights in the range of 600–700 m, and the maximum height is 695 m. Slope design plays a key role in engineering design and construction. However, most of the “high dam and large reservoir” projects in China are located in the central and western regions, such as the Yangtze River, Jinsha River, Lancang River, Yalong River, Dadu River, Yellow River, and Hongshui River, which are close to the Qinghai-Tibet Plateau. In these areas, the terrain is elevated, the mountains are high, the valleys are deep, the neotectonics and the seismic activities are strong, the geological disasters are frequent, the topographical and geological conditions are extremely complex, and engineering high slope stability is particularly important. During the construction and operation of hydropower projects, there have been many serious slope instability incidents that have caused casualties, increased investments, and extended construction periods. These incidents have affected the normal and safe operation of the projects. High slope stability problems have affected and restricted the development of hydraulic resources and the process of engineering construction. Therefore, it is of great significance to summarize and draw lessons from the design experience of hydropower high slopes in China. Combined with engineering practices in China, this paper systematically summarizes and integrates the existing research results and design experience. Additionally, design procedures and methods for Chinese high slope hydropower projects are discussed for reference.

2. Geological basis of slope design: A slope structure type system

2.1. Basic concepts

A slope structure is a kind of existing form or structure style that represents the stable state of a slope geological body. It is related to the material type of the geological body (rock or soil), the development degree of the weak structural surface, and the combination characteristics of the slope surface, degree of fragmentation, deformation and failure characteristics, and other structural factors. For a rock slope, the weak structural surface development degree and its combination with the slope surface are the main structural factors affecting the slope stability. A weak structural surface refers to a geological structural surface with a certain length, thickness, and low mechanical strength. This mainly includes a layer of sedimentary rock, weak strata, a weak interlayer and sedimentary discontinuity, foliation and a schistosity plane of metamorphic rock, a contact zone of magmatic rock and a flow layer of eruptive rock, faults, an interlayer dislocation zone or compression zone, large weathered unloading fissures, weathered dikes, and weathered mud interlayers. In engineering practice, a geological structural surface whose length is more than 30 m is generally called a weak structural surface. The combined relationship between the occurrence of a weak structural surface and a slope surface affects or controls the stability of a rock slope. There are five types of combination relationships between a weak structural surface and a slope surface. (1) Forward relationship: The angle between the strike of the layered or non-layered weak structure surface and the slope surface is less than 30°, and the inclination angle of the weak surface is less than the slope angle. The angle between the inclination of the intersection edge line or syncline axis of the two groups of weak structural surfaces and the slope is more than 60°. (2) Oblique relationship: The angle between the strike of the layered or non-layered weak structure surface and the slope is greater than 30° and less than 60°. (3) Lateral relationship: The angle between the strike of the layered or non-layered weak structure surface and the slope is greater than 60°. (4) Reverse relationship: The angle between the direction of layered or non-layered weak structure surface and the slope surface is less than 30°, and the weak surface tendency is opposite to the slope surface tendency. (5) Flat-stack relationship: The inclination angle of the layer or weak structure surface is small, generally not more than 10°.

Research and practice have shown that the slope structure stability formed by the forward relationship is poor, and the slope structure stability formed by other relationships is better.

2.2. Slope structure type

According to the formation type of a slope geological body, the combination relationship between a weak structural surface and a slope surface, the rock mass fragmentation degree,
the deformation and failure characteristics and other factors, combined with engineering landslide and slope case studies, slope structures can be classified into five categories and 21 sub-categories (Table 1).

| Slope structure type       | Slope structure characteristics                                                                 |
|----------------------------|--------------------------------------------------------------------------------------------------|
| I1 Overall block structure | The lithology is hard and complete, cracks are not developed, and no weak structural surfaces are developed. |
| I2 Sub-block structure     | The rock mass or stratigraphic layer is not developed, and no other weak structural surface is developed. |
| II1 Horizontal structure   | Stratum layer or weak structural surfaces are developed, but layers or weak structural surfaces form a lateral relationship with the slope surface, and the angle between strikes is greater than 60°. |
| II2 Reverse structure      | Stratum layer or weak structural surfaces are developed, the layer or weak structural surface has a reverse relationship with the slope, the angle between the strike of the layer or weak structural surface and the slope is less than 30°, the tendency is opposite, and there is no toppling deformation. |
| II3 Flat-stack structure   | Stratum layers are developed, soft rock or weak structural surfaces are generally not developed, strata or weak planes are stacked flat, and the dip angle is generally less than 10° without deformation. |
| II4 Oblique structure      | Stratum layers or weak structural surfaces are developed, and layers or weak structural surfaces form an oblique relationship with the slope. The angle between the strikes is greater than 30° and less than 60°, with opposite inclination and no deformation. When the strata incline to the outside of the slope, lateral structural surfaces are not developed. |
| II5 Double layer structure | As a whole, the stratum can be divided into two parts: a hard layer and a soft layer, which can be divided into two combinations of "upper soft and lower hard layers" and "lower soft and upper hard layers", and there is no tensile deformation. |
| II6 Steeply inclined forward structure of layer or weak surface | A layer or weak structural surface is relatively developed, the strata and the slope form a forward relationship, the angle between the strikes is less than 30°, and the strata dip is greater than 65° as well as greater than the slope angle. There is no tipping deformation. |
| III1 Forward structure of layer or weak surface | The lithology consists of sedimentary rocks, metamorphic rocks and volcanic rocks with various thicknesses, the angle between the bedding strike and the slope strike is less than 30°, the inclination of the bedding plane is greater than 10° and the inclination is smaller than the slope angle, and a layer or weak structural plane develops and forms a potential slip surface. |
| III2 Non forward structure of layer or weak surface | The stratum or rock mass develops non-layered weak structural surfaces, such as faults, long and large unloading cracks, etc. The weak structural surfaces form a forward relationship with the slope surface. Angle between the strikes is less than 30°, and the camber angle of inclined slope is generally greater than 10° and less than slope angle. |
| III3 Wedge forward structure | A wedge-shaped body composed of two sets of weak structural planes intersecting and combining. The intersection of the ridge line is inclined to the outside of the slope, and the inclination angle is smaller than the slope angle. |
III4 Syncline axis forward structure
The axial direction of the synclinal fold axis and the slope surface form a forward relationship. The angle between the synclinal axial inclination and the slope strike is large (more than 60°), and the inclination angle is smaller than the slope angle. The weak strata or structural surface in the synclinal stratum may constitute the arc-shaped sliding wedge.

IV1 Fragmented structure
The fractured rock mass is formed by the intensive cutting of joints and fissures produced by various causes, such as a fault fracture zone, fissure dense zone, strong weathering zone, or strong unloading zone.

IV2 Scattered structure
The characteristics can be summarized as the fully weathered zone and the strong tectonic fracture zone of the rock slope, and the quaternary sediments of various soil slopes are loose or weakly cemented.

V1 Landslide structure
The rock and soil mass of the slope have been damaged by sliding.

V2 Dump structure
The layered rock mass at a certain depth of the upper slope has bending deformation outside the slope, which mostly occurs in the layered reverse structure and the layered steep structure slope.

V3 Buckling structure
The upper rock mass within a certain depth of the slope has creeping deformation along the layered weak stratum or soft structural surface, the lower rock mass bends outwards, which is mostly seen in layered co-directional structural slopes, and the stratum dip is close to the slope angle.

V4 Dangerous rock structure
The soft layer or weak structural surface in the lower part of the slope has compression deformation, and the upper hard rock has tensile crack deformation, forming a large-scale dangerous rock mass, which mostly occurs in the double-layer structure (upper hard and lower soft) slope.

V5 Loose structure
In a deep valley, high ground stress is released, the rock mass rebounds after unloading, or an earthquake occurs. The rock mass generally relaxes and breaks either along the original structural plane or with structural plane opening and dislocation displacement.

V6 Collapse structure
Deformation only occurs in the upper part of the slope, forming collapse dislocation, and there is no through slip surface. This is more common in scattered and fragmented rock and soil slopes.

V7 Flow structure
The soil and rock mass on the slope surface is in a critically stable state, and it can easily flow down the slope under saturated water conditions.

2.3. Slope structure types and stability characteristics
Class I slope: This includes class I1–I2 structure types. The rock mass has no layers or weak structural surfaces. Layers and weak structural surfaces are not developed, such as hard and complete magmatic rock, medium deep metamorphic rock, thick sedimentary rock, and thick volcanic rock. Under natural conditions, landslides rarely occur on the slope, sliding failure rarely occurs on the engineering slope, and the slope is stable as a whole.

Class II slope: This includes class II1–II6 structure types. The layers or weak structural surfaces of the rock mass are developed, the layers or weak structural surfaces and the slope surface form the relationships of transverse, reverse, oblique, flat, or steep, there is no deformation and failure phenomenon, and the slope is basically stable.

Class III slope: This includes class III1–III4 structure types. The rock mass layer or weak
structural surface is developed. The combination of a layer or a weak structural surface and slope surface or the combination of a layer and a weak structural surface group as well as a slope surface constitute various forward relationships. The weak structural surface constitutes the potential slip surface of the slope. Under certain conditions, such as torrential rain, water storage in reservoirs, excavation with cutting or blasting, or earthquakes, there will be a high probability of engineering landslides, and slope stability is generally poor.

Class IV slope: This includes class IV1–IV2 structure types. There is broken rock mass and soil mass, such as fault tectonite in a rock mass, a cleavage zone, a fissure dense zone, a fully strongly weathered rock zone, and a loose soil slope with various causes, which can easily be damaged in a rainstorm, flood discharge, blasting excavation, or other circumstances, and the slope stability is poor.

Class V slope: This includes class V1–V7 structure types. The rock mass has slipped or deformed and is in an unstable state. Under the action of engineering or an earthquake, deformation and failure may be accelerated. The slope is unstable.

3. Slope design goals, processes, and tasks

3.1. Slope design goals
According to the engineering position, slopes can be divided into hub area slopes, reservoir slopes, and downstream river slopes. The hub area slopes are further divided into building foundation slopes and building environment slopes or surrounding slopes. The slope design goal is to meet the requirements of safe project operation and ensure that the slope does not produce harmful deformation and damage. Specifically, a building foundation slope should meet the requirements of both stability and deformation, such as a dam foundation slope, shiplock slope, and hydropower station intake slope. A building environment slope and downstream river slope must meet the stability requirements and allow certain deformation. A reservoir slope is allowed to deform or to have damage when it is confirmed that the damage will not produce harmful surges.

3.2. Slope design process
According to the design process, the hydropower slope design process in China consists of geological research, scheme design, construction design, and operation design (as shown in Figure 1), including four stages and 11 steps.

3.3. Research on slope engineering geology
The task of slope engineering geology research is to identify the structural features of a slope, establish a model of the slope structure, and to evaluate stability of a slope preliminarily in order to provide a basis for the design of the slope engineering scheme. Geological research methods mainly include engineering geological survey specifications, geotechnical test regulations and other relevant technical regulations [4-6]. Research records mainly include comprehensive geological plans, slope geological plans and profiles, survey and test data, and geological reports.

3.4. Study of slope scheme design
Its intention is to propose a specific and feasible design scheme and provide a blueprint for slope excavation and support. According to preliminary geological evaluation, detailed treatment scheme design or monitoring design must be carried out for a hub area slope that cannot meet stability and deformation requirements, a reservoir slope that may cause a harmful surge, and a downstream river slope that may affect the normal operation of hub area buildings. The main slope design methods use quantitative analysis, such as the limit equilibrium method, the numerical analysis method, the model test method, and the methods specified in the slope design code and slope monitoring code [7].
3.5. Study of slope construction design
The construction design stage is a verification process for the design scheme, so the main task is to ensure the safe implementation of the slope design scheme. Slope deformations and failures are often caused by changes of the construction factors, geological conditions, and stability conditions during the construction period. The construction design mainly depends on the geological cataloging and slope system monitoring during construction. By analyzing the behavior of a slope system comprehensively, the stability of the slope is judged, and feedback design is carried out if necessary.

3.6. Study of slope operation design
During the operation stage of a hydropower project slope, especially in the initial stage of operation, due to the influence of reservoir water storage, flood discharge erosion, and atomization precipitation, the stability condition of the slope deteriorates sharply. A slope is the most prone to deformation and failure at this time. Manual inspection and instrument monitoring methods are mainly used to pay close attention to slope monitoring and observation information. Relevant personnel judge the slope stability and instability hazards according to relevant information and carry out a treatment design in a timely manner.

Figure 1. Flowchart of slope design of hydropower project
4. Slope design steps and research content

4.1. Step 1: Identify the basic geological characteristics of the slope
By means of geological survey and investigation, basic geological phenomena such as the stratum lithology, geological structure, groundwater, in-situ stress, weathering are investigated and recorded in detail. It is important to determine the distribution and characteristics of various weak structural surfaces.

4.2. Step 2: Establish the slope structure model and evaluate the stability
(1) The rock integrity, geological structure surface level, and properties, the combination relationships between the weak structure surface and slope surface, deformation and failure phenomena, and weathering unloading characteristics are studied in detail.
(2) The type of slope structure in the engineering area is identified and established. Additionally, the engineering area slope is divided into sections according to the determined slope structure type, and the slope engineering geological map is recorded and compiled in detail.
(3) For slopes with the structures of Class III, Class IV, and Class V, the distribution range, deformation failure mode, possible slip surface, and slip boundary must be further determined. When the test data in the preliminary design stage are insufficient, the value of the structural area can be appropriately reduced according to empirical range value (Table 2).

Table 2. Anti-cut and shear experience value strength of geological structural surface [4]

| Type                  | Anti-cut strength | Shear strength |
|-----------------------|-------------------|----------------|
|                       | Friction coefficient | Cohesion (kPa) | Friction coefficient | Cohesion (kPa) |
| Hard structural plane | Cemented          | 0.80–0.60      | 250–100            | 0.80–0.60     | 0              |
|                       | Without filling   | 0.70–0.45      | 150–50             | 0.70–0.45     | 0              |
| Weak structural plane | Rock fragment     | 0.55–0.45      | 250–100            | 0.50–0.40     | 0              |
|                       | Rock fragments with mud | 0.45–0.35 | 100–50             | 0.40–0.30     | 0              |
|                       | Mud with rock fragments | 0.35–0.25 | 50–10              | 0.30–0.25     | 0              |
|                       | Full mud          | 0.25–0.18      | 5–2                | 0.25–0.15     | 0              |

(4) Based on the type of slope structure and engineering experience, the preliminary evaluation is made according to the geological conditions, which is very important. A Class III structure slope is a potentially unstable slope, a Class IV structure slope is a less stable slope, and a Class V is an unstable slope. These three types of slopes are the main objects of slope design research.
(5) A slope engineering geological report is prepared, and the opinions that can reflect the geological structure characteristics and stability geological evaluation of the slope in detail are prepared.

4.3. Step 3: Determine the safety control standard of slope design
(1) For hub area and downstream river slopes that cannot meet the stability or deformation requirements as well as reservoir landslides that may cause harmful surges due to instability, stability demonstration and design plan demonstrations will be carried out. Safety control standard or safety factor of slope design is related to the type, grade, and working condition of slope engineering. (2) It is challenging to determine the design safety factor reasonably. According to Chinese engineering experience, the China hydropower slope design code provides a design safety factor range value based on the lower limit solution of the limit equilibrium method (Table 3). In practical application, the design safety factor should be comprehensively evaluated and determined according to the investigation degree of the slope geological conditions, the rationality of the parameter value, the importance of the slope, and the hazards of slope instability. This design safety factor can also be higher or lower than the specified value.
Table 3. Slope design safety factors for hydropower and water conservancy projects [7].

| Type Level | Type A hub area slope | Type B reservoir slope | Type C river slope |
|------------|-----------------------|------------------------|-------------------|
|            | permanent condition   | transient condition    | accidental condition |
| I          | 1.30–1.25             | 1.20–1.15              | 1.10–1.05         |
| II         | 1.25–1.15             | 1.15–1.05              | 1.05              |
| III        | 1.15–1.05             | 1.10–1.05              | 1.00              |

4.4. Step 4: Draw up the slope design scheme
(1) Regarding excavation design, for a slope around a hub area and the Class III, IV, and V structural slopes in a reservoir area, depending on the distribution location, scale, thickness, influence degree, and instability hazard degree of rock and soil mass, all or part of the excavation can be adopted, that is, the so-called reducing load on slope and pressing toe of slope.
(2) The drainage design is generally a preset condition for the hub area slope, and drainage measures are required. Priority should be given to the reservoirs and river slopes.
(3) For reinforcement design, the reinforcement range should be reasonably determined according to the location, scale, and depth of the unstable rock and soil mass, and the form and type of the reinforcement structure should be reasonably selected.
(4) Based on the above work, a support and reinforcement scheme is proposed. The proposed scheme should contain as many feasible schemes as possible, including natural state, excavation without support, and excavation with support. The support scheme should include the combination of various reinforcement forms, various reinforcement structure types, various arrangement positions, and various structural parameters.

4.5. Step 5: Slope stability analysis and calculation
This step includes confirming the failure mode and boundary conditions, calculating the parameter values, selecting the analysis method, and calculating the stability.
(1) According to slope structure type, the potential slip block’s slip surface and its boundary conditions are further confirmed, and the parameter values are calculated. Two or more representative geological sections are provided.
(2) The limit equilibrium method is one of the main methods for slope stability analysis. The slope design code recommends the simplified Bishop method, Jambu method, Morgenstern-Price method, and transfer coefficient method [7]. For a slope with obvious lateral constraints, a three-dimensional calculation model should be used. Two or more calculation and analysis methods should be adopted for level I and II slopes, including the numerical analysis method for deformation and stability analysis and a comprehensive evaluation of the slope deformation and sliding stability.
(3) For the stability calculation of the proposed design scheme, it is necessary to go through several iterations of the process of stability calculation, including (step 5) comparing the calculation results with the design safety factor, (step 3) adjusting the scheme, (step 4) stability calculation, and (step 5) again, until one or more design schemes that meet the design safety factor requirements appear.

4.6. Step 6: Determine and refine the design scheme
(1) Among the design schemes meeting the safety control standards, a relatively better scheme is determined with comprehensive analysis through further comparison of the economic, safety, and construction conditions.
(2) The slope is further divided in detail, and the design plan is refined for key reinforcement
areas and key reinforcement objects. The specific excavation layout, drainage layout, reinforcement type, and parameters are determined. In addition, it is necessary to analyze the excavation and support sequence. For the blasting and excavation conditions, the principles that are generally followed are: drainage first, then excavation; load reduction first, then reinforcement; underground first, then ground first.

4.7. Step 7: Predict the slope system behavior and determine the monitoring design scheme
(1) The uncertain factors in the slope design plan are evaluated including the geological uncertainty, construction method uncertainty, and design scheme uncertainty. Additionally, the abnormal phenomena that may occur during slope construction are predicted, such as the slope stress concentration, the deformation position and its magnitude, and the possible influence and harm of slope failure with engineering construction.
(2) A monitoring scheme design should be carried out for parts that may have stress concentrations and large deformations. Due to the perfect drainage system in the hub area slope, monitoring items focus on potential slip surface displacement, surface deformation and structural stress; for landslides or unstable slopes in the reservoir area, the groundwater and surface deformation are mainly monitored.

4.8. Step 8: Analysis of geological information and slope behavior during the construction period, and Step 9: Continued construction or completion of the slope.
The slope construction stage is officially entered in step 8. The main work includes geological cataloging and analysis and monitoring the data collection and analysis.
(1) The key points of the geological logging are weathering and unloading, water seepage and gushing, a soft layer or a weak structural surface, deformation and failure, landslide resurrection, and other geological phenomena [8]. Based on this, we compare the previous geological research and analyze the changes and possible effects of the geological conditions.
(2) The existing monitoring data are collected and sorted to compare and predict the slope system behavior.
(3) The changes in the geological conditions and the monitoring data are comprehensively analyzed, these changes are compared with previous geological judgments (step 2) or system behavior predictions (step 7), and the slope stability is evaluated.
(4) Monitoring and early warning should be carried out for slopes with prominent stability problems, which may threaten construction safety or cause casualties and huge property losses after damage. According to factors such as the slope engineering category, safety level, deformation, and failure mode, the safety alert level and the corresponding warning standard are determined.
(5) When the slope is completed, construction quality inspection and completion acceptance shall be carried out. In addition, according to the actual deformation and stability of the slope, the long-term monitoring work is arranged.

4.9. Step 10: Analysis of slope operation patrol and monitoring information, and Step 11: Continuance of slope operation
At the initial stage of reservoir impoundment and power station operation, due to the deterioration of the slope working conditions and the sharp adjustment of stress, slope deformation and instability are frequent. Over time, most of the slopes will gradually stabilize, and some slopes will experience a longer period of deformation and convergence, which requires monitoring and patrolling.
(1) Close attention should be paid to the slope deformation and the failure phenomenon, the causes and the development trend of the deformation and failure should be analyzed, and the stability and instability risk of the slope should be evaluated. If slope deformation is stable within the controllable range, no treatments should be adopted (step 11).
(2) For a sub area slope for which the deformation is large and may affect the normal operation of a building, or a reservoir landslide for which the deformation and instability may cause great harm, corresponding measures should be taken according to damage level and emergency state, including additional monitoring items, renovation design, and operation
warning.

(3) According to the hazard object and degree, operational warnings can adopt emergency measures such as limiting the reservoir water level, limiting flood discharge or power generation, and announcing warnings around the reservoir and evacuating people.

5. Conclusion

(1) Compared with other engineering fields, because the working environments of hydropower engineering slopes are related to water, these slopes can easily be affected by reservoir storage and water level fluctuations, spillway and ship lock overflows, and power station flood discharge scouring and flood discharge atomization precipitation. The stability conditions are poor, and the slope design is special and difficult.

(2) Slope structural characteristics are the basis of slope design. According to the established five major structural types and standards, it is an important task for slope design to identify the structural types of slopes in engineering areas. Key objects of a design are the poorly stable Class III and Class IV engineering slopes and the unstable Class V engineering slopes.

(3) Based on slope structure characteristics and engineering experience in China, a systematic design method for China hydropower high slope engineering is summarized and proposed, including four stages and 11 steps, which is complete in structure, clear in content, and is easy to use in practice.

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