Comprehensive evaluation on the stability of deposit slope from reservoir bank

Qi Yang¹,², Zai qian Chen¹,², Dong dong Zhang¹,², Ya Shi¹,²

¹Power China Guiyang Engineering Corporation Limited, Guizhou Province, Guiyang550081,China ;
²HydroChina Guiyang Engineering Corporation Geotechnical Engineering Company Limited,Guizhou Province,Guiyang550081,China)
†Corresponding author: Qi Yang; yangqi80h@163.com

Abstract. In the construction of hydropower station in high mountains and canyons of southwest China, it is common to encounter deposit slopes of scattered collapse and debris flow. The deposit is formed by multi-phase and multi-genesis. Their material composition is dominated by crushed and lumpy rock and soil, and their structure is relatively dense. In natural conditions, the failure mode is mostly small-scale collapse, which has little influence on the project. With the construction of hydropower station, some deposits will be partially or completely submerged after reservoir impoundment. In reservoir impoundment condition, the stability of the deposit body decreases, and the local instability of the deposit body may cause the overall instability of the bank slope, resulting in surges and thereby endangering the safety of the dam and residents nearby.

In this paper, a typical reservoir bank of a hydropower station in western China is taken as an example. The seepage characteristics and stability of the deposit body are calculated by using Geostudio series software. On this basis, the three-dimensional numerical simulation of the deformation of the deposit body is carried out by using FLAC-3D software. Through the comparison and analysis of the calculation results, the stability, deformation development trend and failure mode of the deposit body are summarized. It can provide reference for the comprehensive determination, monitoring arrangement and treatment of the similar deposit body.

Key words: Deposit slope in reservoir bank: Percolation features; Deformation features; Comprehensive evaluation on stability

1. Introduction

1.1 Topography, scale and morphological characteristics

The accumulation body is located on the left bank of the middle and upper section of the reservoir area, about 60km away from the river course of the dam site. This section of the river is relatively straight. The river generally runs from north to south and the river bed elevation is about 1820m. The river channel incises strongly, which result in a deep canyon landform in the valley. The bank slope is high and steep with a maximum elevation difference of 1700m. According to Fig.1 and Fig.2, deep gullies are developed on both sides of the accumulation body, and the front riverside slope is relatively steep and multiple gullies are developed. Influenced by gully cutting, the integrity of slope was damaged to a certain extent. The top elevation of the accumulation body is 2100m~2200m, which is 200m~300m higher
than the riverbed. The riverside slope is relatively steep with a natural slope of 50~60° and leading edge height of 100m~150m. The topography is relatively flat with a natural slope of 15~30°. The length of the accumulation body along the river is about 1.7km, and the trailing edge is about 400m~600m away from the river channel. The total volume is about 60 million cubic meters.

![Fig.1 Landform of the deposit slope](image1)

![Fig.2 Engineering geological plane maps of deposit slope](image2)

According to the distribution range and influence of the accumulation body, the accumulation body can be divided into I and II two areas (Fig.1). Area I is located in the upstream of the accumulation body and has a relatively large area with a total volume of about 40,000,000m³. Area II is located on the downstream side of the accumulation body and has the same composition as area I, but its scale is smaller and its trailing edge is relatively closer to the riverbed. The total volume is about 20,000,000m³. As the scale of area II is smaller and the stability is relatively better, so in this paper the stability study mainly focuses on the calculation and analysis of area I.

1.2 Material composition and structural characteristics of the accumulation body

The results of surface investigation and exploration data show that the material composition of the accumulation body is mainly composed of mixed soil with fine-grained gravel, the lithology of the debris is slate, and the filling fine-grained material is mainly clay and silty sand. A typical section of the accumulation body is shown in Fig.3. According to drilling data and surface survey, the accumulation body can be divided into three layers (Fig.3).

The upper part of the accumulation body is mainly composed of colluvial lithoclasts. The lithoclasts are mainly composed of slate, limestone, sandstone and marble, which are gray and grayish white. The content of the block stone is about 5%~25%, and the particle size is 20~30cm, up to 35cm, and is angular. The detritus content is about 30%~40%, the particle size is generally 6~15cm, angular shape. The content of gravel is about 40%~55%, the particle size is 1~5cm. The fine gravel is formed by weathering slate. The coarse gravel is marble, sandstone, slate, limestone weathering, angular ~ sub-angular shape and contains a small amount of soil and sand with loose structure.

In the middle of the accumulation body, there is a layer of earth-yellow gravel sand layer. The upper part of the sand layer is relatively uniform, medium and fine sand. The lower part of the sand layer contains gravel, the content is about 10%, the particle size is generally 1~5cm. The lithology is subangular, angular limestone, sandstone.

The lower part of the accumulation body is gravel soil containing rubble stone, which is yellowish brown, grayish white, grayish yellow, etc. The gravel composition is mainly
sandstone, slate, limestone and marble, etc. The particle size of broken stone is generally 5~20cm, mostly angular, and the content is not uniform, generally about 30~40%. The particle size of the gravel is generally 0.5~4cm, dominated by sub-angular shape, and the content is about 50~60%. The rest are sand and soil, containing a small amount of argillaceous, and local argillaceous cemented closely.

Fig.3 Geological section map of SN2-SN2’ of the deposit slope

Fig.4 The boundary of the soil layer of the deposit slope

1.3 Deformation characteristics of the accumulation body

The field investigation shows that the accumulation body is basically stable in the natural state. However, due to the strong downward cut of the river reach and steep bank slope, combined with the effect of river scour, cut out slope toe and running water on the slope, the front edge of the high and steep slope presents the phenomenon of over-collapse (Fig.5 and Fig.6).

Fig.5 Steep highway slope at the front of the accumulation body

Fig.6 Typical soil layer boundary on the opposite side of the accumulation body

2. Analysis of the formation mechanism of the accumulation body

The glacier movement formed the ice water deposit here, the river cut down to form a high and steep slope, and then the downstream deposit blocked the river, resulting in the alluvial fine sand layer on the upper part of the ice water deposit. After that, rivers continued to cut down, and the rock mass at the top of the slope collapsed and migrated over the alluvial sand layer under the long-term weathering. The accumulation body is the result of the long-term development through the above river cutting, glacier movement, river blocking and siltation in the lower reaches, and slope rock mass collapse, migration and accumulation. Fig.6 shows a typical soil boundary on the opposite side of the accumulation body.

3. Stability calculation and analysis of the accumulation body
SN2-SN2 'and SN4-SN4' profiles were selected for calculation. The SEEP/W module of Geostudio software was used to conduct finite element analysis on the seepage field characteristics of the accumulation body under the present water level and when the reservoir impoundment reaches 1925m. The seepage calculation results were taken as the groundwater level conditions. Slope/W module of Geostudio software was used to calculate and analyze the stability of the accumulation body under different working conditions. According to the calculation results of limit equilibrium stability, the stability of the accumulation body under various working conditions was analyzed. The stability and safety of the accumulation body were evaluated according to the calculation results of Mogenstern-Price method.

3.1 Load case and load combination
According to the "Design specification for slope of hydropower and and water conservancy projects" (DL/T5353-2006), the natural conditions and conditions of reservoir impoundment and earthquake are mainly considered. The seismic intensity in the area where the accumulation body is located is seven degree. According to the "Seismic ground motion parameters zonation map of China" (GB18306-2015), within the reservoir area, the peak ground motion acceleration exceeding 10% of the probability in the base period of 50 years is 0.123g, and the peak ground motion acceleration used in calculation is 0.123g. The classification and safety factor of the accumulation body are determined according to the "Classification & design safety standard of hydropower projects" (DL5180-2003) and "Design specification for slope of hydropower and and water conservancy projects" (DL/T5353-2006).

3.2 Determination of calculation parameters
According to the test results, combined with the composition of the accumulation body and its geological characteristics, the investigation of the failure mode of nearby similar landslides and the dip angle of the sliding surface, and the existing empirical data of the simulation of the landslide, after comprehensive analysis, the suggested values of the physical and mechanical parameters of the soil of the accumulation body are put forward as shown in Table 1.

| Rock and earth mass          | Unit weight γ (kN/m²) | Cohesion c (kPa) | Angle of internal friction φ (°) | Hydraulic conductivity y (cm/s) |
|-----------------------------|-----------------------|-----------------|----------------------------------|---------------------------------|
|                            | Natural condition     | water-saturated condition | Natural condition | water-saturated condition | Natural condition | water-saturated condition | Natural condition | water-saturated condition | Natural condition | water-saturated condition | Natural condition | water-saturated condition |
| Collapse slope gravel soil  | 21.1                  | 21.2             | 40                               | 20                             | 36                             | 32                             | 1.5×10⁻²               |
| Gravel soil                 | 15.5                  | 16.5             | 30                               | 13                             | 18                             | 16                             | 7.9×10⁻⁴               |
| Carbaceous gravel soil      | 20.6                  | 21.0             | 50                               | 22                             | 38                             | 33                             | 3.2×10⁻⁴               |
3.3 Analysis of seepage field characteristics of the accumulation body

In addition to the basic characteristics of common mountain deposits, the reservoir bank deposits have their particularity as the hydrogeological environment in the slope has been changed by the reservoir impoundment. The essential reason of slope deformation caused by the change of reservoir water level is the interaction between water and rock in slope, that is, Water-rock interaction leads to the decrease of shear strength parameters and the change of seepage pressure. Combined with the geological exploration data of accumulation body, SEEP/W module of Geostudio software was used to analyze the seepage of SN2-SN2 'and SN4-SN4' at the normal water level of river before impoundment and when the reservoir water level was impoundment to 1925m respectively. The analysis results are shown in Fig. 7~Fig.10.

According to the investigation data, no groundwater was found in the SN2-SN2 'and SN4-SN4' profiles. Fig.7 and Fig.8 are the simulation curves of the groundwater level under the normal water level of the reach. Fig.9 and Fig.10 are the simulation curves of the groundwater when the water was impounded to 1925m. The permeability of the overburden of the accumulation body is strong to medium, while the underlying bedrock layer is weak. In addition, although there is abundant rainfall, the water-bearing medium has poor water content, so the initial groundwater level is relatively gentle. When the water is impounded to 1925m, the reservoir water level recharges the groundwater level in the slope, but the permeability of the bedroom layer is poor, and the groundwater level rises slowly, so the lower water level of the former slope inclines inward.

| Argillaceous | 25.6 | 26.8 | 100 | - | 34 | - | 5.8×10⁻⁶ |

**Fig.7** simulation curve of groundwater level in profile SN2-SN2’

**Fig.8** simulation curve of groundwater level in profile SN4-SN4’
3.4 Stability analysis and evaluation of accumulation body

As mentioned above, the rock-soil structure of accumulation body is a mixture of block gravel and fine grained soil. The underlying bedrock of the accumulation body is slate, which is exposed by drilling. There is no weak intercalated layer in the exploration borehole, so it can be inferred that no large overall deformation occurred after the formation of the accumulation body. However, due to the strong erosion and reconstruction of the river, the front of the accumulation body has been in the process of deformation and reconstruction for a long time, and the bank slope is deep and the slope is steep, so the local deformation and failure signs of the front of the accumulation body are obvious. Therefore, the overall stability of the accumulation body and the local stability of the leading edge were considered to calculate the accumulation body stability. The trailing edge boundary and bottom boundary of the accumulation body were taken as the calculation range of the overall stability. The stability coefficient calculated by specifying the sliding surface was taken as the evaluation basis of the overall stability. The deformation range and stability coefficient of the front of the accumulation body were obtained by searching the most unfavorable slip surface, which were used as the basis for evaluating the local stability of the accumulation body.

3.4.1 Calculation of overall stability

According to the position and representation of each exploration section in the accumulation body, SN2-SN2' and SN4-SN4' were selected as the profiles for stability calculation. Fig.11 and Fig.12 are the calculation bar diagram of the stability of the deep sliding surface of accumulation body.

![Fig.9 Simulation curve of groundwater level in profile SN2-SN2' at storage to 1925m](image)

![Fig.10 Simulation curve of groundwater level in profile SN4-SN4' at storage to 1925m](image)

![Fig.11 Deep Sliding Bar chart of SN2-SN2' Profile](image)

![Fig.12 Deep Sliding Bar chart of SN4-SN4' Profile](image)
Table 2. Calculation results of the overall stability of the accumulation body

| Calculated section | slip surface | Calculation method        | Calculated working condition |  
|--------------------|--------------|---------------------------|-------------------------------|
|                    |              |                           | Natural condition | Natural +Seismic Condition | Impoundment condition | Impoundment +Seismic Condition |
| SN2- SN2'          | Deep integral sliding | General slice method | 1.425 | 1.171 | 1.383 | 1.111 |
|                    |              | Bishop method             | 1.555 | 1.290 | 1.536 | 1.240 |
|                    |              | Janbu method              | 1.416 | 1.155 | 1.388 | 1.107 |
|                    |              | Morgenstern-Price method  | 1.534 | 1.280 | 1.519 | 1.240 |
| SN4- SN4'          | Deep integral sliding | General slice method | 1.681 | 1.361 | 1.489 | 1.168 |
|                    |              | Bishop method             | 1.804 | 1.480 | 1.636 | 1.298 |
|                    |              | Janbu method              | 1.626 | 1.314 | 1.477 | 1.157 |
|                    |              | Morgenstern-Price method  | 1.828 | 1.511 | 1.656 | 1.329 |

The overall stability calculated from the representative profile of the accumulation body was checked, and the stability calculated under natural conditions and normal water storage conditions were shown in Table 2.

3.4.2 Calculation of local stability

In addition to the calculation of the overall stability of the accumulation body, considering that the shallow surface of the accumulation body was controlled by micro-topography and there were signs of collapse in the front edge of the slope, in order to analyze the influence of water impoundment on the stability of the accumulation body, the initial water level and the water impoundment to 1925m were selected for stability calculation and analysis. The most dangerous slip surface search technology is used to track and search the potential slip surface in the accumulation body, and identify the potential damage body, and make a comprehensive judgment on the stability evolution of the accumulation body.

Fig. 13 Searching for sliding surface under initial water level of SN2-SN2'profile

Fig. 14 Searching for sliding surface at Storage to 1925m of SN2-SN2'profile
Through automatic search, the stability results of the initial water level and the condition of normal water storage to 1925m are shown in Table 1-5. The most dangerous slip surface searched is shown in Fig.13 ~ Fig.16. The reservoir impoundment will lead to the change of local stress state and the corresponding change of local stability. After the local failure of the sliding body, progressive failure will continue to occur at the back. As shown in Table 3, the leading edge of the accumulation body has the worst local stability no matter at the initial water level or when the water is stored up to 1925m, that is, the leading edge is the site most prone to creep.

Table 3. Calculation results of accumulation body stability

| Calculate section | slip surface | Calculation method | Calculated working condition |
|-------------------|--------------|--------------------|-------------------------------|
|                   |              | Natural condition  | Natural +Seismic Condition    | Impoundment condition  | Impoundment +Seismic Condition |
| SN2-SN2’          | Automatically search for initial water level | General slice method | 1.184                         | 1.024                     |                               |
|                   |              | Bishop method      | 1.229                         | 1.049                     |                               |
|                   |              | Janbu method       | 1.182                         | 1.022                     |                               |
|                   |              | Morgenstern-Pri ce method | 1.220                        | 1.040                     |                               |
| SN4-SN4’          | Automatically search at storage to 1925m | General slice method | 0.897                         | 0.837                     |                               |
|                   |              | Bishop method      | 0.991                         | 0.941                     |                               |
|                   |              | Janbu method       | 0.951                         | 0.891                     |                               |
|                   |              | Morgenstern-Pri ce method | 0.990                        | 0.940                     |                               |
| Method                          | Morgenstern-Pierce method | General slice method | Bishop method | Janbu method | Morgenstern-Pierce method |
|--------------------------------|---------------------------|----------------------|---------------|--------------|--------------------------|
|                                | 1.180                     | 0.929                | 0.986         | 0.959        | 0.981                    |
|                                | 1.040                     | 0.859                | 0.916         | 0.889        | 0.911                    |

### 3.4.3 Stability analysis and evaluation

The stability analysis of the accumulation body is in accordance with the "Classification & design safety standard of hydropower projects" (DL5180-2003) and the "Design specification for slope of hydropower and and water conservancy projects" (DL/T5353-2006). The results were analyzed as follows:

1. **Overall stability**
   - Under natural conditions, the overall stability coefficient of the deposit is between 1.419 ~ 1.831, and the whole body is in a stable state. When the water is stored to the water level of 1925m, the overall stability coefficient is between 1.386 ~ 1.659, and the overall stability is in a stable state, but the stability coefficient decreases. Considering the influence of design earthquake, the stability coefficient under natural conditions is between 1.158 ~ 1.514, which is stable on the whole. When the water is impoundment to the level of 1925m, the stability coefficient is between 1.110 ~ 1.332, and the whole is in a stable state, but the stability coefficient is significantly reduced.

2. **Local stability of leading edge**
   - Under natural conditions, the local stability coefficient of the front of deposit is between 1.167 ~ 1.229, and the front is in a stable state. When the water is impoundment to the water level of 1925m, the stability coefficient is between 0.897 ~ 0.991, the leading edge is in an unstable state locally, and the potential deformation and instability area is below the elevation of 1950m. Considering the influence of design earthquake, the stability coefficient is between 1.022 ~ 1.049 under natural conditions, and the leading edge is in a basically stable state. The stability coefficient is between 0.837 ~ 0.941 when the water level is impoundment to 1925m, and the leading edge is in an unstable state locally.

### 4. Three-dimensional numerical simulation analysis of accumulation body deformation

#### 4.1 Establishment of computational model

The three-dimensional numerical model of the accumulation body was established mainly based on the engineering geological plan, section and borehole data, and the rockfall gravel soil, pebbled silty clay and bedrock were considered.
Fig. 17 Three-dimensional calculation model diagram of accumulation body

The range of the model is 1400m in the X direction (near the parallel valley direction), 790m in the Y direction (near the vertical valley direction), and 640m in the Z direction (starting from 1750m elevation). The model adopts three-sided constraints, namely, one-way constraints on both sides of the X direction, one-way constraints on both sides of the Y direction, one-way constraints on the bottom side of the Z direction, and free fronting surface on the slope surface.

4.2 Selection of mechanical parameters

The deposit body consists of bedrock and loose deposits. In the calculation model, the required volume modulus and shear modulus are converted from the elastic modulus and Poisson's ratio. The values of mechanical parameters in the calculation model are shown in Table 4. The conversion formula of volume modulus ($K$) and shear modulus ($G$) is as follows:

$$K = \frac{E}{3(1-2v)}$$
$$G = \frac{E}{2(1+v)}$$

In the formula, $K$ is the volume modulus, $G$ is the shear modulus, $E$ is the elastic modulus, and $v$ is the Poisson's ratio.

| rock and earth mass conditions | unit weight $\gamma$ (kN/m$^3$) | Angle of internal friction $\varphi$ (°) | cohesion $c$ (kPa) | volume modulus $K$ (GPa) | shear modulus $G$ (GPa) | hydraulic conductivity (cm/s) |
|-------------------------------|----------------------------------|-----------------------------------------|-------------------|--------------------------|--------------------------|-------------------------------|
| Collapse slope gravel soil    | Natural condition                | 21.1                                    | 36                | 40                       | 0.47                     | 0.33                          | $1.5 \times 10^{-2}$          |
|                               | water-saturated condition        | 21.2                                    | 32                | 20                       | 0.38                     | 0.26                          |                               |
| Carbaceous gravel soil        | Natural condition                | 20.6                                    | 38                | 50                       | 0.40                     | 0.27                          | $3.2 \times 10^{-4}$          |
|                               | water-saturated condition        | 21.0                                    | 33                | 22                       | 0.33                     | 0.22                          |                               |
| Argillaceous                 | Natural condition                | 25.6                                    | 34                | 100                      | 14.20                    | 6.50                          | $5.8 \times 10^{-6}$          |

4.3 Calculation results and analysis

Natural conditions and 1925m elevation water level were considered in the three-dimensional simulation calculation of accumulation body. In the above two working conditions, the stress
field and displacement field of the accumulation body are simulated, and then the deformation and failure characteristics of the accumulation body are analyzed.

4.3.1 Deformation characteristics of accumulation body under natural conditions

1. Stress field analysis

Under natural conditions, the stress field distribution of the deposit is shown in Fig.18 and Fig.19. According to the calculation results, under natural conditions, the stress field of the deposit is similar to that of deep valley bank slope, and its main characteristics are as follows: The maximum principal stress of the accumulation body is compressive stress (Fig.18). The maximum principal stress in the slope body is nearly horizontal, from the interior of the slope body to the open surface, and the maximum principal stress deflects and turns parallel to the slope surface. With the increase of depth, the maximum principal stress increases, and the maximum principal stress in the slope is about 5~10MPa. The maximum principal stress of the surface layer is only about 0.3MPa, while that of the surface layer is less than that of the middle and deep layer.

The minimum principal stress distribution is similar to the maximum principal stress distribution. As shown in Fig.19, the minimum principal stress is generally low, ranging from 0.5 ~ 1.5MPa in the middle and deep sections. The minimum principal stress on the surface of the accumulation body is extremely low. Although the surface stress is generally compressive, there may be some tensile stress areas locally.

Fig.18 Maximum principal stress diagram of the accumulation under natural conditions (unit: Pa)

Fig.19 Minimum principal stress diagram of accumulation body under natural conditions (unit: Pa)

2. Deformation analysis

The total displacement of the accumulation body is shown in Fig.20. It can be seen from the figure that, under natural conditions, the deformation of the accumulation body is mainly located at the steeper leading edge of the accumulation body area I, and the total displacement is nearly 9cm. These large deformation parts have a steep slope, and the slope bodies on both sides of them have collapsed to form gullies (Fig.1), resulting in three empty parts. Under the action of gravity stress, the slope not only produces the displacement towards the valley, but also produces the compression deformation towards the valley and the vertical direction. The simulation results are in good agreement with the deformation status of the accumulation body.
As shown in Fig.21, the horizontal displacement (Y direction) of the steep slope at the leading edge of accumulation body I area is large, and the displacement value is about 5cm. The horizontal displacement of other parts of the accumulation body is small, about 2cm. The vertical direction (Z direction) of the accumulation body is mainly subsidence compression deformation, which changes with the elevation in area I. The vertical displacement of the accumulation body varies from 6 cm to 1cm from top to bottom (Fig.22).

To sum up, under natural conditions, the deformation of the accumulation body under the gravity stress field of valley bank slope is mainly concentrated in the front edge of area I. Its displacement is mainly horizontal (Y direction) and vertical (Z direction) displacement in the air direction.
According to the shear strain calculation results (Fig. 23), the deformation of these high and steep free face is relatively concentrated, and there is the possibility of local small-scope collapse failure.

4.3.2 Deformation characteristics of accumulation body under normal storage condition of 1925m

1. Stress field analysis

Fig.24 distribution of maximum principal stress under water storage condition (unit: Pa)

Under the water storage condition of 1925m, the stress field distribution characteristics of the accumulation body are similar to those under natural conditions (Fig.24, Fig.25). Compared with natural conditions (Fig.18, Fig.19), the maximum and minimum principal stresses on the surface of the accumulation body are smaller, and the distribution range is also slightly different. Among them, the range of minimum principal stress on the surface of the accumulation body increases and the stress value further decreases. This change is mainly related to the uplift force and seepage force caused by the rising water level.

Under the condition of water storage at 1925m, tensile stress is generated locally due to the decrease of principal stress. Combined with the field investigation, the leading edge platform of the accumulation body may have local tensile stress. Influenced by the topography and landform of the accumulation body, the tensile stress is unfavorable to the stability of the slope body, which may lead to tensile failure at the front of the accumulation body.

2. Deformation analysis

The three-dimensional simulation results of the total displacement of the accumulation body are shown in Fig.26. The deformation of the accumulation body is mainly concentrated in area I. Compared with the calculation results under natural conditions, the deformation range of the accumulation body increases and the displacement further increases under the water storage condition. It can be seen from the figure that the deformation at the central leading edge of the accumulation body in area I is the most prominent, and its maximum total displacement reaches 37cm. In general, the deformation range of the accumulation body is dustpan type, from the leading edge to the middle and rear, and the displacement value gradually decreases with the increase of the elevation.

According to the total displacement figure, the local large deformation area at the front edge of the accumulation body is mainly concentrated in the part with the elevation below 2000m and the maximum depth is about 30-40m. Under the condition of 1925m water storage, the front of the accumulation body may suffer local instability failure due to excessive
deformation and poor stability. The location of the potential deformation zone of the accumulation body obtained by numerical simulation is basically consistent with the result of limit equilibrium analysis, but the trailing edge of the deformation site obtained by numerical simulation is slightly larger.

Fig. 26 Total displacement distribution of accumulation under water storage condition (unit: m)

Fig. 27 Horizontal displacement distribution diagram of accumulation body under water storage condition (Unit: m)

Fig. 28 Distribution diagram of vertical displacement under water storage (unit: m)

Fig. 29 Shear strain rate of Sn2- Sn2' profile under water storage condition

Fig. 27 and Fig. 28 show the calculated results of displacement in various directions of the accumulation body. It is not difficult to find that, at the normal storage level of 1925m, the deformation in area I of the accumulation body is mainly manifested as horizontal displacement (Y direction) and vertical displacement (Z direction) along the direction of the blank surface. Combined with the shear strain calculation results of the accumulation body (Fig. 29), it can be seen that under the condition of water storage, the deformation of the
accumulation body mainly begins to creep from the foot of the leading edge slope, and with
the aggravation of deformation, local failure of the leading edge may occur.
In short, affected by the rise of the reservoir water level, the deformation of the accumulation
body increases and the stability decreases. The front edge of the accumulation body may be
the first to undergo instability failure. With the instability and slip of the leading edge,
traction failure may occur in the middle and rear parts, which leads to the further expansion of
deformation failure range.

5. Comprehensive evaluation of accumulation body stability
According to the investigation and analysis, the stability analysis and the three-dimensional
numerical simulation analysis, the formation and deformation characteristics of the deposit
are recognized as follows:
(1) With the strong uplift of the Qinghai-Tibet Plateau, the river cutting, glacier movement,
river blocking and siltation, slope rock and soil mass collapse, migration and accumulation
repeatedly and continuously formed the present accumulation body finally. The accumulation
body is composed of rock mass, gravel soil and silt soil, and the structure of slope body is
relatively complex.
(2) Based on the survey results and the analysis of the engineering geological conditions of the
accumulation body, the deformation of the accumulation body is mainly controlled by the
unloading and gravity action caused by the valley cutting. At present, the overall stability of
the accumulation body is good, and there is no macro deformation sign of possible overall
instability, but there is local deformation and failure in the front edge of the accumulation
body. Due to the strong cutting of the valley, the height of the accumulation body was more
than 100m, and the slope reached 50~60°. According to the morphology of the accumulation
body, the leading edge area I has been in a critical state, which is bound to cause some
deformation adjustment.
(3) Considering the influence of reservoir water storage and earthquake, the limit equilibrium
method is adopted to calculate and analyze the stability of the accumulation body under
various working conditions. The limit equilibrium stability analysis results show that the
overall stability coefficients of the accumulation body are 1.416-1.829, 1.115-1.511,
1.383-1.656 and 1.107-1.329, respectively, under the four working conditions of natural state,
natural state with seismic condition, impoundment to 1925m and impoundment to 1925m
with seismic condition. Although the overall stability coefficient of the accumulation body
decreases under the influence of adverse factors, they are all in a stable state.
Under the above four working conditions, the calculated local stability coefficients of the
front of the accumulation body are 1.167~1.229, 1.022~1.049, 0.897~0.991 and 0.837~0.941,
respectively. The calculation results show that the accumulation body is in a stable state under
natural conditions and in a basically stable state under the design earthquake, but the front of
the accumulation body is in an unstable state under the impoundment and the adverse effects
of impoundment and earthquake.
From the analysis of limit equilibrium stability, it can be seen that with the impoundment of
the reservoir, the reservoir water level will replace the unloading action and the gravity action
and become the key factor to control the deformation and stability of the accumulation body.
In addition, the calculation results show that the local deformation and failure range of the
front edge of the accumulation body is below the elevation of 1950m.
(4) The three-dimensional numerical simulation shows that the stress field of the accumulation body has similar characteristics to the stress field of the general deep river bank slope. Under natural conditions, the surface stress value of the accumulation body is low. Due to the water impounding and the water level rising, the main stress field on the surface of the accumulation body changes, the minimum principal stress range increases, and local tensile stress area may appear.

In natural conditions, under the action of gravity stress, the deformation of the accumulation body occurs along the air direction, mainly located in the steep part of the front of the accumulation body. Among them, the deformation of the accumulation body in area II is small, while the deformation of the front of the accumulation body in area I is obvious, and the maximum displacement is about 9cm.

Under the condition of 1925m water storage, the deformation range of the accumulation body increases, and the displacement increases further. The deformation range of the accumulation body is dustpan type, from the leading edge to the middle and rear, and the displacement value decreases gradually with the increase of the elevation. The deformation at the steeper part of the central front of the accumulation body in area I is the most prominent, and its maximum total displacement reaches 37cm, which is mainly manifested as horizontal displacement (Y direction) and vertical displacement (Z direction) along the direction of the blank surface. Combined with the comprehensive analysis of displacement and shear plastic deformation, the large deformation area of accumulation body in area I is mainly located in the part below 2000m elevation and the maximum depth is about 30-40m. The deformation and failure range is basically consistent with the analysis results of limit equilibrium stability. Affected by the rise of the reservoir water level, the leading edge failure of the accumulation body will creep due to the softening and shear deformation. With the aggravation of the deformation, the local leading edge failure will appear. The deformation and failure of the leading edge may produce traction effect, which leads to the traction failure of the upper slope.

References
[1] Design specification for slope of hydropower and and water conservancy projects (DL/T5353-2006)
[2] Seismic ground motion parameters zonation map of China (GB18306-2015)
[3] Classification & design safety standard of hydropower projects (DL5180-2003)