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Stability of Huangtupo Riverside Slumping Mass II# under Water Level Fluctuation of Three Gorges Reservoir

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ABSTRACT: After the normal operation of the Three Gorges Reservoir, the water level of the reservoir will fluctuate periodically. Water level fluctuation will soften the rock and soil on the banks, induce underground water fluctuation and decrease the shear strength of rock soil on the banks, and in turn affect the landslide stability. The Huangtupo (黄土坡) landslide is a typical large and complex landslide in the Three Gorges Reservoir region. In particular, the stability of its riverside slumping mass has a great stake. On the basis of the analysis of engineering geological condition and formation mechanism of the Huangtupo landslide, the authors established the 2D finite element model of riverside slumping mass II# and selected proper mechanical parameters of the rock. With the GeoStudio software, according to the reservoir running curve, the simulation on coupling effect of seepage field and stress field was conducted in 7 different modes in a year. The results showed that: ① Huangtupo landslide is a large and complex landslide composed of multiple slumping masses, which occurred at different phases. Before reservoir impoundment, it was stable; ② it is quite difficult for riverside slumping mass I# and II# to slide as a whole; ③ the stability coefficient of riverside slumping mass II# changes with the reservoir water level fluctuations. The minimum stability coefficient occurs 48 days after the water level starts to fall and the moment when the water level falls by 11.9 m. Landslide monitoring result is consistent with the numerical simulation result, which shows that although the reservoir water level fluctuation will affect the foreside stability of the landslide and induce gradual damage, the riverside slumping mass II# is stable as a whole.

KEY WORDS: operating condition, Three Gorges Reservoir, riverside slumping mass II#, Huangtupo landslide, finite element method, landslide stability.

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INTRODUCTION

After the normal operation of the Three Gorges Project, the water level of the reservoir now fluctuates periodically within the range of 145–175 m every year. Water level fluctuation will soften the rock and soil on the banks, induce underground water fluctuation and decrease the shear strength of rock soil on the banks, and in turn affect the landslide stability. The Huangtupo landslide is a typical large and complex landslide in the Three Gorges Reservoir region, and its stability can not only affect people's lives and property, but also concerns the safety of shipping on the Yangtze River. Therefore, it is necessary to conduct an in-depth research on the stability of the Huangtupo landslide under the normal operation of the reservoir.

With respect to the study on landslide stability under the condition of reservoir operation, apart from the study on the impact of rising water level on landslide stability through maximum equilibrium theory and numerical simulation with the water-soil coupling effect (Liu C H et al., 2005), researchers have also conducted an in-depth study on landslide stability during the drawdown of water level (Liao et al., 2005; Liu X X et al., 2005; Tang and Zhang, 2005; Chai and Li, 2004), and paid more attention to the impact of water level fluctuation on landslide stability (Ding et al., 2004; Mantovani and Vita-Finzi, 2003; Zhu et al., 2002; Hewitt, 1998). The water level fluctuation ranging from 145 to 175 m is the focus of our concern. There are few studies on the actual water level fluctuations under the operation condition of Three Gorges Reservoir (Hu et al., 2007; Hu, 2006), and lack of achievements in systematic study. In particular, the study on landslide stability under the practical long-term operation condition of the Three Gorges Reservoir has just begun.

This article focuses on the large and complex Huangtupo landslide, taking the coupling effect of stress field and seepage field into account, evaluating the deformation rules and stability changes of riverside slumping mass II# based on the analysis of engineering geological conditions of the Huangtupo landslide and practical operation condition of the Three Gorges Reservoir, and provides reference to an evaluation on the long-term stability of large and complex landslides under long-term practical periodical water level fluctuations.

ENGINEERING GEOLOGICAL CONDITION OF HUANGTUPO LANDSLIDE

Basic Features of Huangtupo Landslide

The Huangtupo landslide is developed in slip stratum of the Middle Triassic Badong Formation Section II and Section III, mainly composed of mud rock, pelitic siltstone and muddy limestone. It is a complex landslide formed after multiple slumps. The foreside of the landslide is submerged in the river at an elevation of 50–70 m, and the elevation of the backside is about 600 m, covering an area of 1.358 km^2 with a volume of 6 934.1×10^4 m^3. Divided by Sandaogou, the foreside in the west is slumping mass I, above which is Garden Spot landslide; the foreside in the east is slumping mass II, above which is Substation landslide (see Figs. 1 and 2). Garden Spot landslide and Substation landslide belong to bedding rock landslide. Two slumping masses are located in the main area of the foreside of Huangtupo landslide, with steep slope, intense human activities and poor stability. In recent times, local shallow slides happen frequently, among which the slides of Erdaogou and Sandaogou in 1995 had caused huge disasters. The impoundment of Three Gorges Reservoir has also directly affected the stability of 2 slumping masses, with particular influence on the stability of slumping mass I foreside.

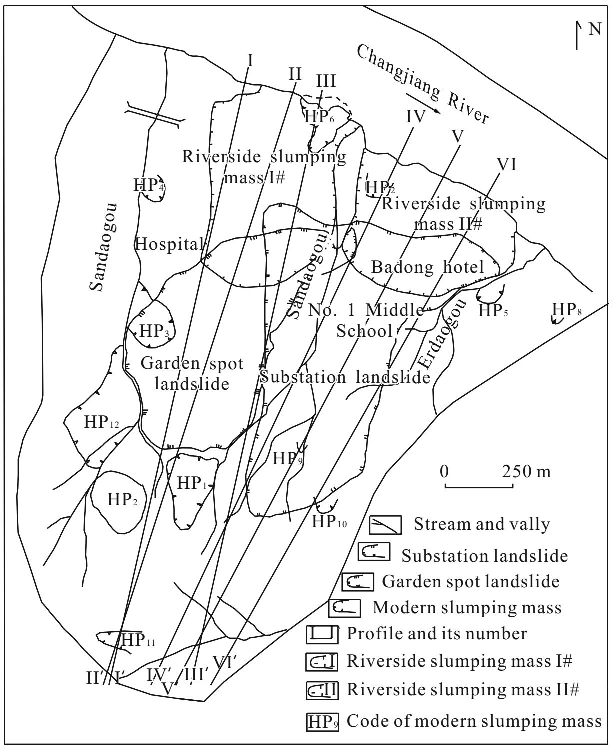

Figure 1. Engineering geological plan of Huangtupo landslide.

Garden Spot landslide covers an area of 32.6×10^4 m^2, with a volume of 1 352.9×10^4 m^3. The plane of Substation landslide is in the shape of "boot", covering an area of 38.1×10^4 m^2 with a volume of

1 333.5×10^4 m^3. The foreside of the landslides lies over the riverside slumping mass. The slide body is composed of T_2b^{3-1} cataclastic rock and rock fragments with limestone and argillaceous limestone, and its medium part is T_2b^2 purple mudstone, pelitic siltstone, cataclastic rock, rock block and rock fragments. The slide belt consists of T_2b^2 brown silty clay, containing angular gravel and pebbly silty clay. The slide bed of Substation landslide is mainly composed of T_2b^2 purple mudstone, pelitic siltstone and T_2b^{3-1} dolomitic limestone, limestone and dolomite.

The eastern boundary of slumping mass II extends along the west of Erdaogou upwards to Badong Hotel and county government, and its western boundary is connected to slumping mass I at shallow part based on the bedrock of Sandaogou. The backside of slumping mass II is covered by Substation landslide (Fig. 2), at an elevation 210–250 m or so. The elevation of its foreside is 50–80 m. Its eastern part is 380 m long and western part is 510 m long. Its width gradually increases from backside to foreside, with backside width at 400 m and foreside width at 650 m. Slumping mass II covers an area of 32×10^4 m^2, with average thickness at 61.11 m, maximum thickness at 91.84 m, minimum thickness at 35.44 m, and volume at 1 992×10^4 m^3. The steepness of the terrain decreases from foreside to backside, and forms a gentle slope platform at the elevation 190–210 m with average gradient of 17°. The platform is connected to gentle slope by steps. Slumping mass II is composed of artificial backfill, gravel soil and rock fragments, containing gravel (pebble), silty clay, cracked stone, cataclastic rock and rock block. The bottom slide belt is generally 1–3 m thick, containing compact, slightly wet and plastic silty clay, muddy limestone and gravel, most in the angular and sub-angular shape, few in the sub-rounded shape, with polished surface and crushed trace at local parts.

The Huangtupo landslide is composed of 4 ancient slumping masses and several modern slumping masses. Riverside slumping masses have undergone 4 large-scale deposit terms, i.e., 40×10^4–38×10^4, 31×10^4–30×10^4, 22×10^4–18×10^4 and 15×10^4–13×10^4 a. The Substation landslide occurred in 19×10^4 to 13×10^4 a. The Garden Spot landslide was formed later than the Substation landslide.

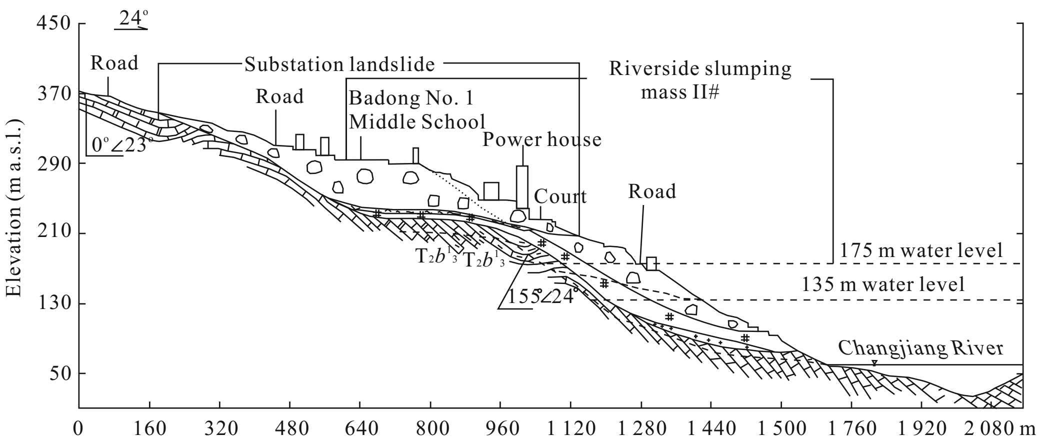

Figure 2. *v-v'* geological profile of Huangtupo landslide.

Formation Mechanism and Evolvement Process of Huangtupo Landslide

During mid-late Middle Pleistocene, because of strong crust uplifting and stream trenching, the Huangtupo area formed into high and steep slope composed of upper soft rock (T_2b^2), medium hard rock (T_2b^{3-1}) and lower soft rock (T_2b^{3-2}). During the long geologic period, under the various geologic forces such as the self-weight of rock slope, tectonic movement and rock weathering, the lower T_2b^{3-2} rock first slumped, steepening the medium rock slope, which slumped and distorted accordingly. While T_2b^2 rock slumped and deposited towards valley and gradually weakened its own gravity (volume), the blocking effect of medium T_2b^{3-1} rock ledge to upper soft rock (T_2b^2) grew weaker and weaker. The gradual accumulation of elastic strain energy of the rock ledge ultimately resulted in sudden destruction, formed

Substation landslide and Garden Spot landslide, and transformed the slope from high attitude to low attitude. Huangtupo landslide has formed an inflection point at the elevation of 200 m, below which the slope is in the unstable state, resulting from the continuous trenching of streams after the slope took shape.

Qualitative Analysis on the Stability of Huangtupo Landslide

After the Substation landslide and Garden Spot landslide took shape, the landslides suffered from erosion and damage for a long time. The slide part was split up, the slide bed was in the shape of waves or steps, and local area was upturned, which countered against the overall sliding of the landslide. Recently, the deformation and damage frequently occurs in the medium landslide platform with strong human engineering activities, and steep zones of surrounding valleys and roads. The deformation and damage is mainly about creeping slide, fractures and collapse at local areas, and the stability of the Huangtupo landslide depends on the stability of the riverside slumping mass.

The riverside slumping mass has suffered erosion, damage and human transformation for a long term. The composition of the landslide has suffered damage during multiple periods and appeared to be pieces and fragments. Therefore, it is quite difficult for riverside slumping mass I# and II# to slide as a whole. The contact surface between slumping mass bottom and bed rock is in the shape of waves or steps, with upturns in local areas, which can resist the slide of upper rock deposit and counter against the overall sliding of the landslide. Recently, the deformation of riverside slumping mass I# and II# at shallow layer frequently occurs during flooding and the rainy season. The foreside of the slumping mass is along the river. Under the influence of dramatic water level fluctuations, the slope is likely to slump, deform and collapse.

NUMERICAL SIMULATION MODEL AND SIMULATION METHOD

Establishment of Mechanical Model

According to geographical analysis, the foreside of riverside slumping mass II# suffers from great impact of reservoir water level fluctuations. Therefore, the profile of riverside slumping mass II# was selected to establish a two-dimensional geo-mechanical model and conduct numerical simulation analysis. The left and right boundaries of the landslide are subjected to the horizontal restraints, and the lower boundary is subjected to the vertical constraint. Seepage boundary: the left boundary is constant water head boundary, the right boundary is changing water head boundary, and the lower boundary is confining boundary. See Fig. 3 for finite element calculation meshes.

Simulation Scheme

Reservoir water-level running curve

The normal water level of the reservoir is 175 m. During the operation period of the project, the reservoir water level fluctuates periodically ranging from 145–175 m every year. See Fig. 4 for reservoir water-level running curve.

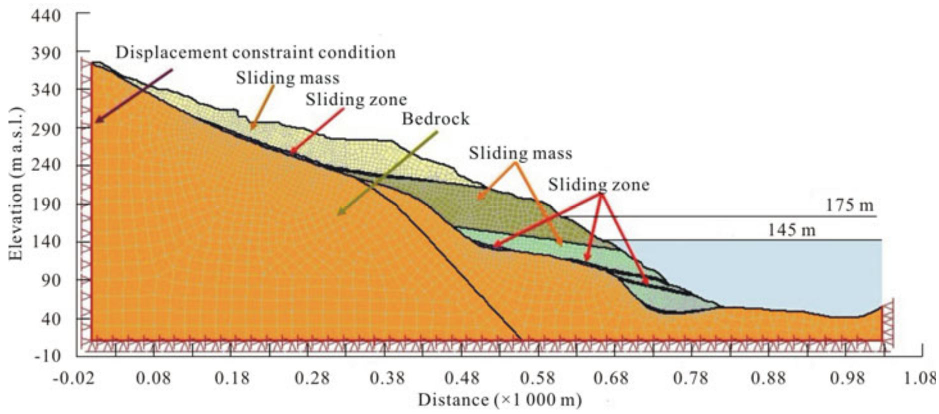

Figure 3. 2D numerical simulation meshes.

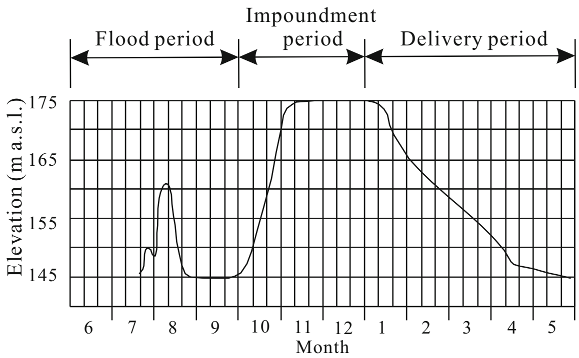

Figure 4. Reservoir water-level running curve.

Simulation scheme

On the basis of the above reservoir water-level running curve, we start simulation from the lowest steady water level during flood season, count one year of fluctuation cycle, and determine the following simulated conditions.

(1) At 145 m water level, lasting 0.111 year (0–41st day);

(2) From 145 m rising to 175 m, lasting 0.083 year (41st–70th day);

(3) At 175 m steady water level, lasting 0.167 year (70th–132nd day);

(4) From 175 m dropping to 145 m, lasting 0.333 year, when the simulated water level dramatically and slowly draws down (132nd–253rd day);

(5) At 145 m steady water level, lasting 0.25 year (253rd–344th day);

(6) From 145 m rising to 162 m, lasting 0.028 year (350th–355th day);

(7) From 162 m dropping to 145 m, lasting 0.028 year (355th–365th day).

The software for finite element calculation is GEOSLOPE. This software can be applied to calculate the coupling effect of seepage field and stress field. Mohr-Coulomb constitutive model is selected according to the simulation scheme for 2-D finite element simulation analysis.

Mechanic parameters

The simulated physical and mechanical parameters of rock body are confirmed according to the Investigation Report on Engineering Geology of Huangtupo Landslide (Table 1).

Table 1 Mechanical parameters of the rock body

Parameters	Elastic modulus (MPa)	Poisson's ratio	Density ($kN·m^{-3}$)	Cohesion (kPa)	Friction angle (°)	Permeability coefficient (m/d)
Bedrock limestone	5.1E+04	0.21	27.6	700	54.0	0.002
Sandy mudstone of slide bed	1.63E+04	0.3	26.8	980	44.2	0.000 1
Fracture rock of slide body	1.7E+04	0.25	25.6	174	34	5.65
Cataclastic rock of slide body	6.8E+03	0.28	24.0	68	26	6.75
Clay and gravel of slide belt	2.566E+01	0.35	22.0	19	16	0.34
Gravel soil of slide body	2.56E+03	0.32	23.5	20	19	7.17

LANDSLIDE STABILITY ANALYSIS

Analysis of Numerical Simulation Results

According to the water-level fluctuation curve of Three Gorges Reservoir, the simulation results on the 40th, 41st, 70th, 100th, 132nd, 165th, 180th, 202nd, 253rd, 344th, 355th and 365th days have been analyzed. The water level on the 40th day has been considered as the initial water level.

Analysis of stress field at the initial water level of 145 m

As shown in Fig. 5, at the initial water level of 145 m, the maximum X-displacement of riverside slumping mass II# occurred at the foreside of the landslide, and maximum value is 0.223 8 m. The negative value of displacement occurred in front of the slope behind the area with positive displacement, and its maximum value (absolute value) is -0.435 1 m. The displacement vector at the foot of the slope turned upwards. The displacement of the back of the slope body generally points downwards and sideways.

As shown in Fig. 6, at the initial water level of 145 m, at the foreside, backside and local central part, the obvious changes of slope belt and material property have led to greater strain at *X* direction.

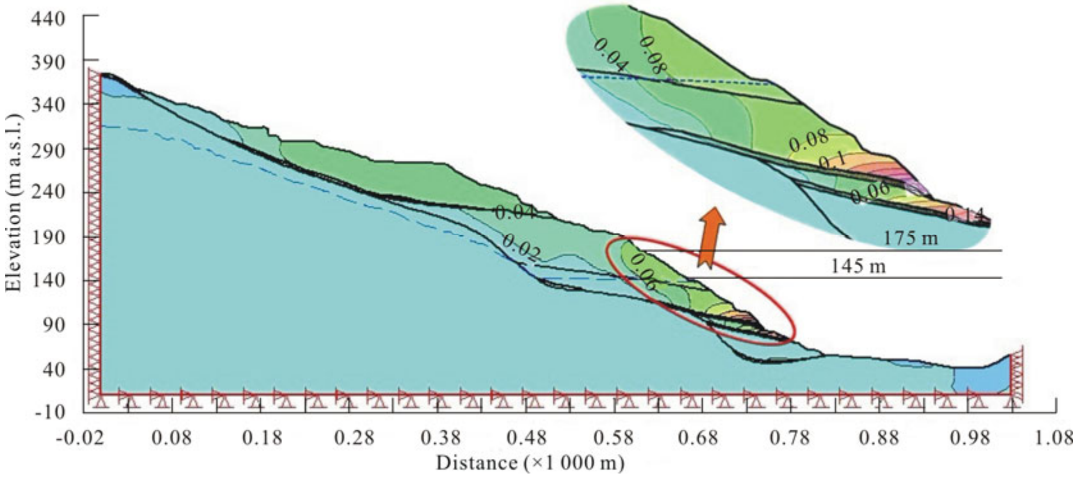

Figure 5. *X*-displacement contour of landslide under reservoir water-level 145 m.

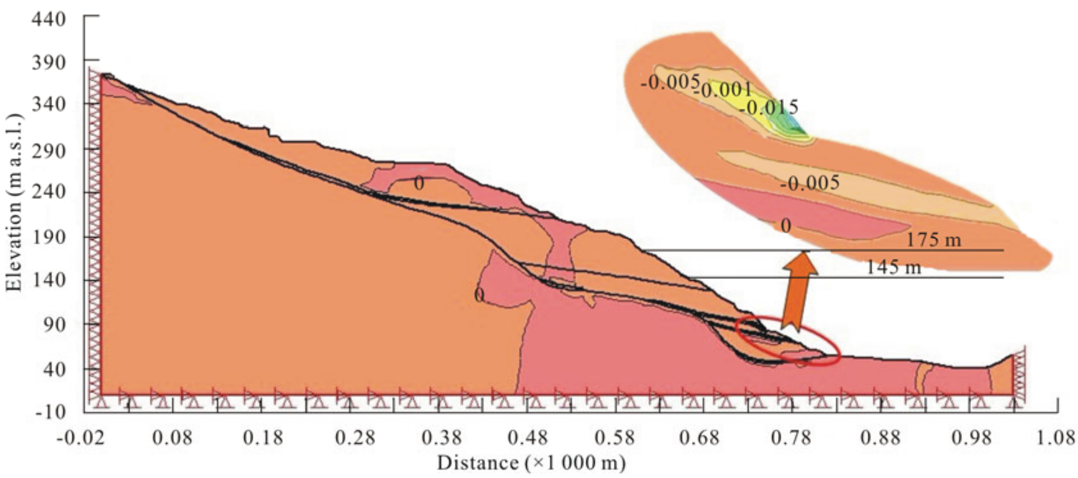

Figure 6. *X* strain contour of landslide under reservoir water-level 145 m.

Deformation analysis with changing water level

To carefully study the changing rules of slope belt and slope body with water level fluctuations, three typical nodes have been selected at the foreside and backside of the landslide, slide body and slide belt (see Fig. 7). The three nodes are 123, 191 and 238, respectively.

Figures 8–10 are the displacement curves of typical nodes on the profile of riverside slumping mass II#.

We can arrive at the following conclusions after analyzing the above 3 displacement curves.

(1) The displacement changes of nodes at the saturation region are consistent with fluctuations of water level, i.e., as the water level rises, the displacement values increase; as the water level falls, the displacement values decrease. This regularity is quite clear and obvious.

(2) The maximum displacement of the landslide occurs at the foreside and foot of the landslide.

(3) Node 238 is in the unsaturated region. During 40–41 days, the displacement value decreased, which is contrary to the displacement changes of nodes at the saturation region.

(4) The displacement fluctuation of Node 238 is more obvious than that at the saturation region.

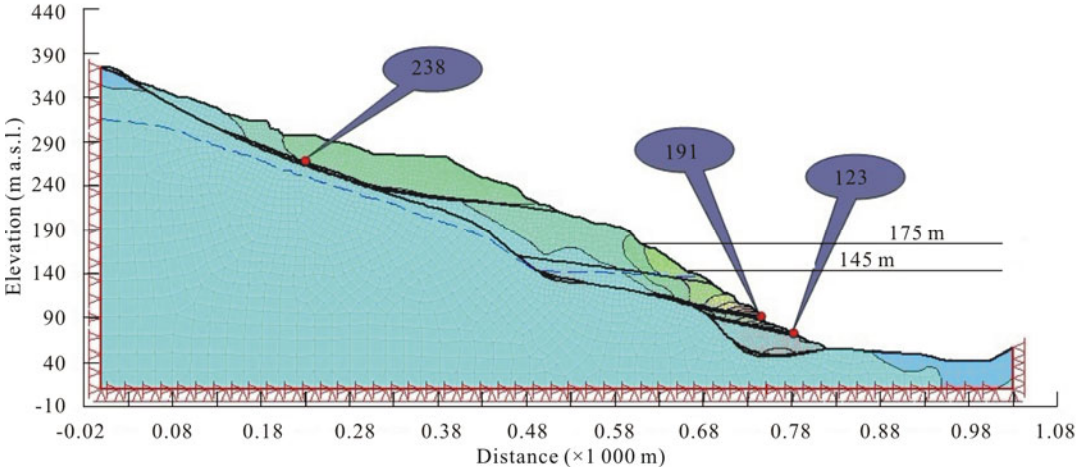

Figure 7. Key node position.

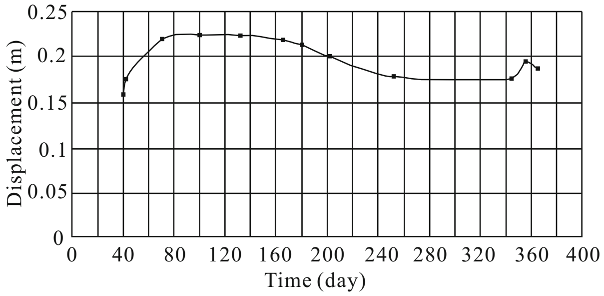

Figure 8. *X* displacement curve with water-level fluctuation at Node 123.

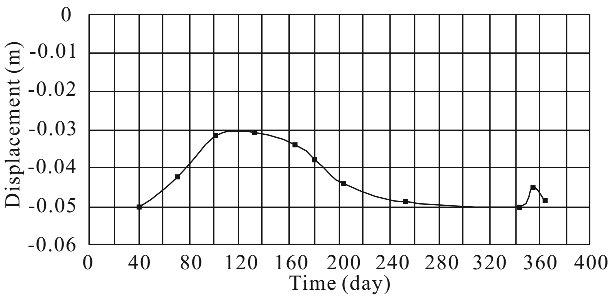

Figure 9. *X* displacement curve with water-level fluctuation at Node 191.

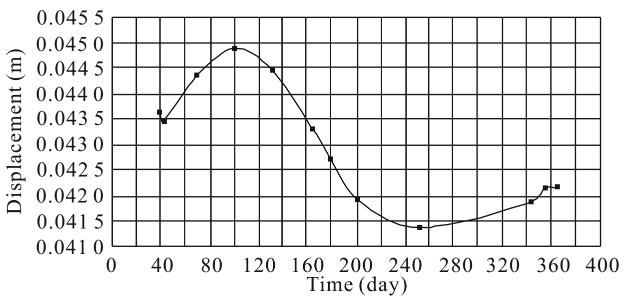

Figure 10. *X* displacement curve with water-level fluctuation at Node 238.

Analysis on stability coefficient with the changing reservoir water level

On the basis of the coupling analysis on seepage field and stress field, on the II-II' profile of Huangtupo, the stability of the landslide has been analyzed by Ordinary method, Janbu method and Morgenstern-Price method with the water level fluctuations on the 40th, 41st, 70th, 100th, 132nd, 165th, 180th, 202nd, 253rd, 344th, 355th and 365th days. See the result in Fig. 11.

At the initial water level of 145 m, the most unstable region is the foreside of the landslide. The slope toe is under the water, and its stability coefficient is (Morgenstern-Price) 1.025, (Ordinary) 0.927 and (Janbu) 1.013. The stability coefficient tested by Ordinary method is the smallest. Comparing the geologic analysis, the Ordinary method produces the large deviations. According to Morgenstern-Price and Janbu methods, it can be deduced that this landslide is in the less stable state.

The stability status of the landslide under the operation conditions of the reservoir is as follows.

(1) The minimum stability coefficient of riverside slumping mass II# occurs as the reservoir water level falls from 145–175 m, specifically, 48 days after the water level starts to fall and the moment when the water level draws down by 11.9 m.

(2) As the water level rises, the stability coefficient decreases.

(3) As the water level drops, the stability coefficient first decreases and then increases. The drastic decrease of reservoir water level can exert obvious impact on the deformation and displacement of vari-

ous parts of landslide.

The changing stability coefficient of the landslide is inconsistent with the changing seepage vector of the slide body. The reason is that, the pressure of reservoir water on slide body and pore water pressure within the slide body have been taken into account during the calculation process, and the two factors have jointly affected the calculated results. As the reservoir water level rises, the reservoir water outside the slide body supplements the underground water within the slide body; as the reservoir water level falls, the underground water within the slide body supplements the reservoir water. The underground water and reservoir water supplement each other, and the changing rate of reservoir water level is larger than that of underground water level. During the changing process of reservoir water level, the saturation region of landslide is greatly affected by the changing water level, while the unsaturated region is less affected by the changing water level.

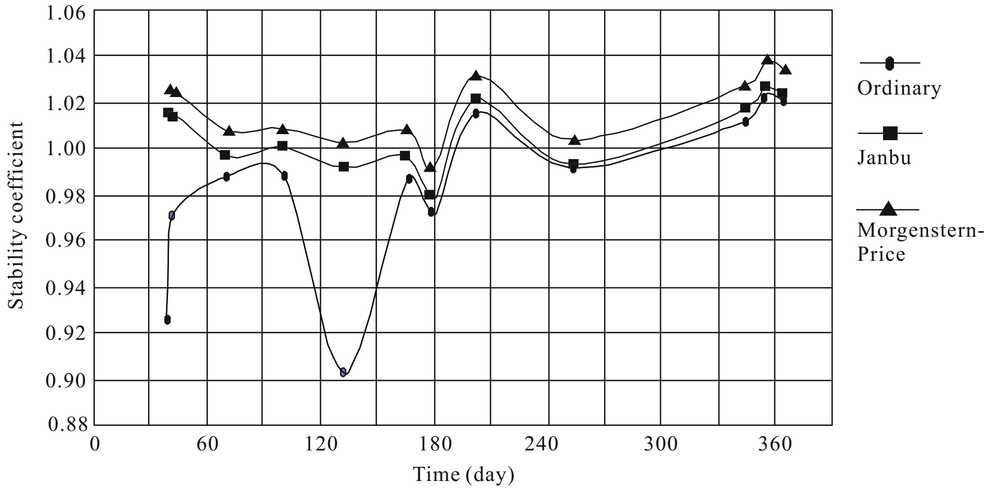

Figure 11. Stability coefficient of riverside slumping mass II# changing with water-level fluctuation.

The foreside slope toe of Huangtupo landslide has the largest displacement. The slide belt and slope toe have the largest strain rate, and these parts are the deformation sensitive regions of the landslide.

To sum up, under the operation conditions of Three Gorges Reservoir, the stability coefficient of Huangtupo riverside slumping mass II# changes with the reservoir water level fluctuations, and the landslide turns to be unstable (stability coefficient lower than 1.0) at some time intervals. The dynamic changes of reservoir water level can directly affect the stability of the landslide, which should be paid attention to during landslide control design.

Analysis on Monitoring Results of Landslide Stability

The monitoring on riverside slumping mass II# includes: GPS Monitoring, Borehole Inclinometer Monitoring, Shallow Underground Water Level Monitoring and Adit Short Baseline Monitoring. According to the monitoring results by Borehole Inclinometer, the foreside of riverside slumping mass II# has not shown obvious slide plane; expect from the foreside with the accumulative displacement at 12.94 mm and accumulative displacement angle within the range of 16° to 48°, the other GPS monitoring points have no obvious deformation since monitoring for the first time; the accumulative displacement of TP4 adit slide belt of riverside slumping mass II# was 3.00 mm in 2005, and no obvious displacement has been monitored afterwards, which indicates that the whole riverside slumping mass II# is basically stable apart from small deformation in the foreside. The monitoring result has confirmed the impact of reservoir operation on the foreside stability of the landslide, which is consistent with the results of numerical analysis.

SUMMARY

(1) Huangtupo landslide is a large and complex landslide composed of multiple slumping masses, which occurred at different phases. It is quite difficult for riverside slumping mass I# and II# to slide as a

whole. As water level fluctuates, the foreside of slump mass is inclined to collapse and deform because of long-term scouring of currents, especially the substantial fluctuations of reservoir water level.

(2) As the reservoir water level rises, the stability coefficient increases; as the water level drops, the stability coefficient of Huangtupo landslide first decreases and then increases.

(3) The stability coefficient of Huangtupo landslide changes with the reservoir water level fluctuations, and the landslide turns to be unstable (stability coefficient lower than 1.0) at some time intervals. As the reservoir water level falls, the minimum stability coefficient of the landslide occurs as the reservoir water level falls from 175 to 145 m, specifically, 48 days after the water level starts to fall and the moment when the water level falls by 11.9 m. The dynamic changes of reservoir water level can directly affect the foreside stability of the landslide, which has been confirmed by the monitoring results on the landslide displacement. Therefore, much attention should be paid to the protection of foreside landslide during landslide control design.

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