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# Mechanism of Reservoir Water in the Deformation of Hefeng Landslide

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**ABSTRACT: The trial impoundment was carried on in Three Gorges Reservoir from September 27, 2008. There were strong deformation and failure in Hefeng (鹤峰) landslide when the reservoir water level descended from the altitude of 173 m. It indicates that the deformation is closely related to reservoir water fluctuation. For this reason, the effect of reservoir water in the deformation was studied, taking Hefeng landslide as an example in this article. First, the geological characteristics and deformation situation of strong deformation region are analyzed to disclose the intrinsic factors and the pattern of the deformation under the condition of water level fluctuation. Second, the stabilities of the landslide are calculated during the rising and descending processes, and the corresponding relationship between reservoir water level fluctuation and landslide deformation is further identified. At last, the seepage fields and the force condition of landslide body below the phreatic line are analyzed to reveal the effect of reservoir water. Moreover, it can be concluded that for better permeable reservoir landslide, during reservoir water rising, the favorable effect of seepage force weakens the unfavorable effect of uplift force, so the rising of reservoir water has little effect on the stability, and no deformation is caused; but during the descending of reservoir water, the unfavorable effect of seepage force is superimposed on the unfavorable effect of the uplift force, which causes the stability to dramatically decrease and leads to the failure of the accumulation body in front of the landslide.**

**KEY WORDS: reservoir water, deformation, stability, permeability, uplift force, seepage force.**

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## INTRODUCTION

Reservoir bank landslide is the general name of slopes that are in a reservoir bank environment with water level fluctuation and have potential slipping trend. It commonly lies in the old landslide body or slope body, and there are no obvious slipping trends and signs before the fluctuation of reservoir water. However, once it happens, the equilibrium relation in the landslide body will change on and on and can eas-

ily lead to landslides. Reservoir water rising makes the soil of reservoir bank soft, and reservoir water descending produces hydrodynamic pressure, which can both induce landslide. Practice shows that majority of reservoir landslides happen in the drawdown of water; however, during reservoir water rising, the front or toe of the slope is gradually immerged and subjected to repeated wave wash, changing the movement condition of groundwater and forming new groundwater pathways, which will also make new landslides or revive old landslides (Wang et al., 2005). The construction of the Three Gorges Project and the water impounding of the reservoir will widely and continuously affect the geological environment around the Three Gorges area, and cause a large number of geological problems. With the rise of water level of the reservoir, there will be 340 public dock berths which belong to the 11 borough or county harbors, 80 town docks and even more exclusive use docks of enterprises to be submerged (Yao et al., 2008). Therefore, studying the effect of reservoir water in reservoir landslides is significant to their prevention and treatment.

## GEOLOGICAL CHARACTERISTICS OF THE STRONG DEFORMATION REGION

Hefeng landslide is located on the south bank of Moxi River that is the secondary branch of the Yangtze River. It was a valley and slope geomorphology. It takes on the shape of circular chair in the plane, which is 750 m wide in front, 440 m in back, and 450 m long and about 3.9 million $m^3$ of volume. The front of the landslide is 149 m high, and the back is 303 m. It is a large-scale old rock landslide, which has been treated to be stable in front. However, during the trial impoundment of the Three Gorges Reservoir in September, 2008, when the reservoir water level descended from the altitude of 173 m, there was strong deformation accruing with water level fluctuation.

The strong deformation region of Hefeng landslide is higher in southeast and lower in northwest with the altitude of 150 m in front and 207 m in back. It has an average of 200 m wide in latitude, 124 m long in longitude, and $24.8\times10^3$ $m^2$. The landslide body has an average of 17.8 m thick, and its volume is 0.442 million $m^3$. It belongs to a medium scale of deep

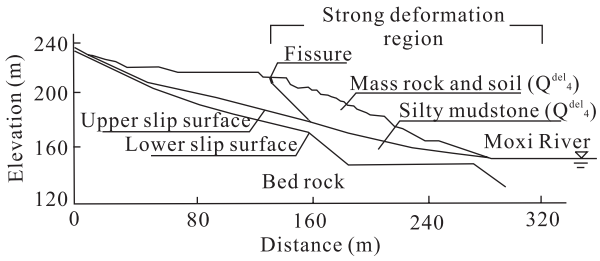


**Figure 1. Main profile of Hefeng landslide.**

seated bedding soil landslide (Fig. 1).

The landslide body of strong deformation region consists of mass rock and soil and cataclastic rock mass, which are permeable. The average thickness of them is respectively 11.08 and 16.59 m, which provides a rich material foundation for the deformation. Clay soil in the mass rock is impermeable. The lower sliding bed is composed of silty mudstone and marlstone, which is also impermeable. As a result, groundwater is prone to influx in the contact zone between rock and soil. It will intensify the weathering of silty mudstone or make silty clay soft and form a weak plane in the landslide body. Thus, all of this is advantage for the formation of slipping surface.

The body of Hefeng landslide is formed by the slump of silty mudstone, marlstone, and limestone of Badong Group ($T_2b$) of Middle Triassic, and they have been gradually disintegrated and weathered into secondary red clay, whose mechanical properties may dramatically decrease when encountering water, and potential slipping surface may develop in the landslide body when reservoir water level rises.

Hefeng landslide is located on the south bank of Moxi River. It is steep in front and back and gentle in middle over the terrain. However, the back of strong deformation region lies in the gentle zone, and its average slope gradient of ground surface is 20° and that of the bedrock is 15°–20°, which is advantageous for the seepage and runoff of surface water and meteoric water. Meanwhile, because of existing of road from Fengjie to Enshi and inside retaining wall, there is free face for the deformation.

## DEFORMATION CHARACTERISTICS OF THE STRONG DEFORMATION REGION

Reservoir water level in the Three Gorges Reservoir descended slowly from the altitude of 173 m on

November 9, 2008, and it is also just on that day when fissures appear in the strong deformation region. In front are shear fractures, and in the back are tension ones. There are 16 monitoring piles, 4 monitoring spots of surface displacement, and 2 horizontal reference spots (Yin et al., 2010). Since the professional monitoring spots were set, 12 of them outside the strong deformation region have had no horizontal and vertical displacement. The remaining four spots inside are HFX07 and HFX09 in back and HFX13 and HFX15 in front; the resultant displacements of which increased with the fluctuation of the reservoir water (Fig. 2).

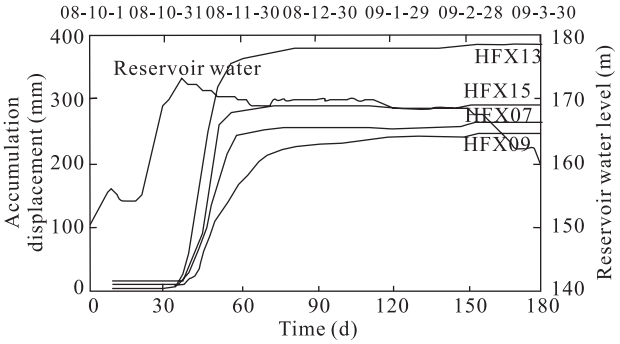


**Figure 2. Curves of the resultant displacement-reservoir water level-time of each spot.**

From Fig. 2, we can see that four monitoring spots started to experience deformation from November 9, 2008. The deformation rate is relatively fast before November 20, 2008, and it gradually becomes slow from November 20 to December 18, 2008. Thereafter, there are still some slight deformations, especially HFX07 and HFX09 monitoring spots in back, the displacements of which have slight increment at the beginning of March, 2009 than two months before. Therefore, the appearing time of deformation is closely corresponding to the time of reservoir water fluctuation, and the slightly increased displacement of HFX07 and HFX09 monitoring spots is related to the frequent precipitation in late spring and early summer (Zhang et al., 2009).

## STABILITY ANALYSIS OF THE STRONG DEFORMATION REGION

According to the geological characteristics of strong deformation region, there are two layers of slipping zone in the landslide body. The upper layer is greatly influenced by the water fluctuation, while the lower one is just mildly affected. Therefore, model building and seepage fields' analysis are just for the upper layer of landslide body (Zhang et al., 2005). The difference value $\Delta F$ between the stability coefficient $F'$ with the effect of reservoir water and the stability coefficient $F$ without the effect of reservoir water is analyzed in order to clearly demonstrate the influence of reservoir water. $\Delta F$ represents the variable quantity of the stability with the effect of reservoir water. "+" means that the stability with the effect of reservoir water increases, and "-" means that it decreases. The rising and descending processes of reservoir water level between the altitude of 158 m in front of the upper layer of the landslide body and 173 m are simulated by the software Geo-slope, and the stability coefficients of different water levels are calculated (Fig. 3) (Li S J et al., 2009; Li M C et al., 2008; Wang et al., 2007).

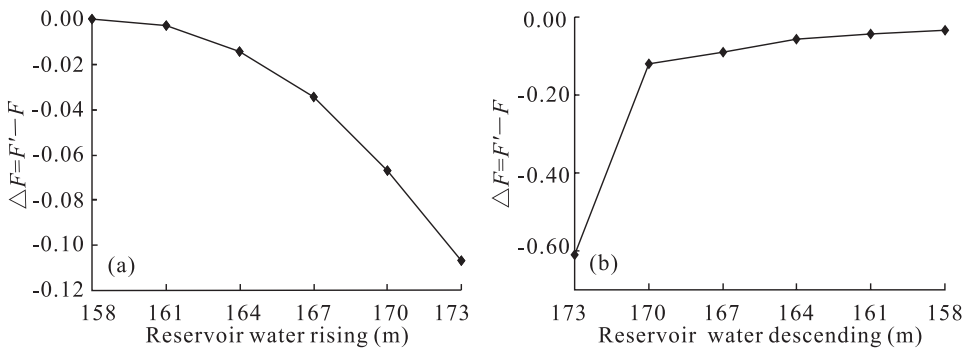


**Figure 3. Changing trends of $\Delta F$ during reservoir water rising (a) and descending (b).**

In Fig. 3, we can see that during reservoir water level rising and descending, the stability of strong deformation region decreases compared with the stability without the effect of reservoir water, which is similar to other reserchers' results (Li et al., 2010; Fu et al., 2008; Zhu et al., 2002). At the rising stage, the absolute value of variable quantity $\Delta F$ is gradually increasing, but its magnitude is not large and less than 0.12. However, during reservoir water level descending, the change of stability can be divided into two stages. The first stage is from 173 to 170 m, namely, initial descending stage. The magnitude of stability decrease compared with the stability without the effect of reservoir water is large, especially at the beginning of reservoir water descending, and the absolute value of $\Delta F$ can reach more than 0.6. The second stage is after reservoir water level descending to the altitude of 170 m. The magnitude of stability decrease compared with the stability without the effect of reservoir water is small; the absolute value of $\Delta F$ is less than 0.15 and slowly tending to zero. Generally, the stability of the strong deformation region is increasing with reservoir water descending. From the analysis above, we know that all of this is consistent with the deformation monitoring result that there is no deformation when reservoir water is rising and when the water level descends from 173 m, and the deformation appears with a fast rate, which slows down when water level descends from 173 to 169 m and gradually stabilizes from then on.

## MECHANISM OF RESERVOIR WATER IN THE STRONG DEFORMATION REGION

The landslide body of strong deformation region consists of mass rock and soil and cataclastic rock mass, which are permeable. Thus, the groundwater table is changing with reservoir water fluctuation, but it lags behind the reservoir water level (Song et al., 2008; Liu et al., 2005). SEEP/W program in Geo-slope software is carried out to simulate the seepage fields in the landslide body during the rising and descending processes of reservoir water level (Fig. 4). In addition, the force condition of landslide body below phreatic line is analyzed (Fig. 5).

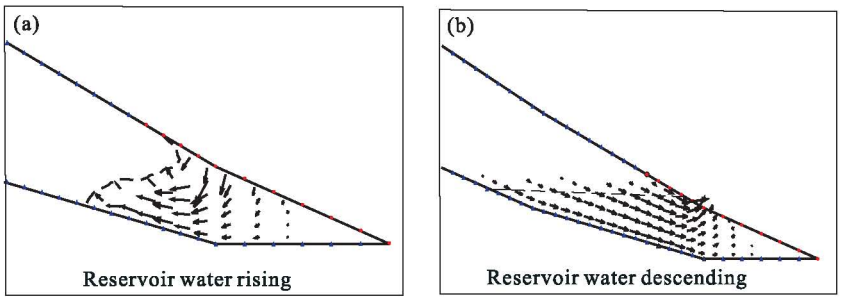


**Figure 4. Seepage fields in landslide body during reservoir water rising (a) and descending (b).**

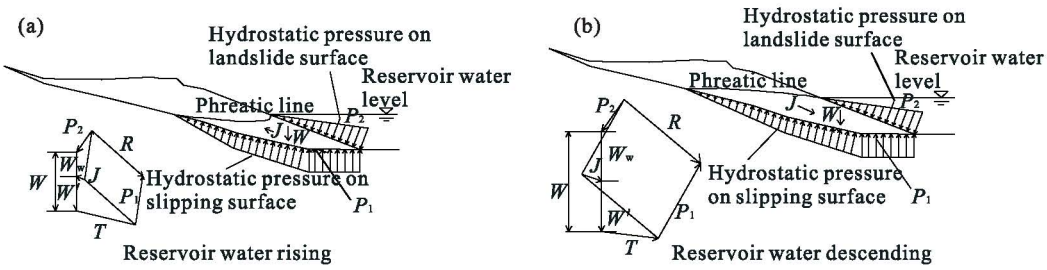


**Figure 5. Force condition of landslide body below phreatic line during reservoir water rising (a) and descending (b). $P_1$. hydrostatic pressure on slipping surface; $P_2$. hydrostatic pressure on landslide surface; *J*. seepage force in the landslide body below phreatic line; *W'*. actual volume weight of landslide body below phreatic line; $W_w$. weight of water below phreatic line; *W*. saturation weight of landslide body below phreatic line; *T*. residual thrust force of landslide body above phreatic line to landslide body below; *R*. resultant force in landslide body below phreatic line.**

From the force analysis in Fig. 5, it can be seen that the action of hydrostatic pressure of reservoir water is equivalent to the action of uplift force and seepage force for the landslide body below the phreatic line during the rising and descending processes of reservoir water level (Jian et al., 2009; Lu, 2002). The uplift force decreases the actual volume weight of the landslide body and leads to the decrease of anti-sliding force; thus, it is unfavorable to the stability. However, the effect of the seepage force needs to be considered separately.

During reservoir water rising, from the distribution of seepage field in Fig. 4a, it can be seen that the seepage force directs inside the landslide body. Its normal and tangential component forces on the slipping surface both increase the antisliding force. Thus, under the combined action of uplift force and seepage force, though the stability of strong deformation region decreases, the magnitude is small, and there is no deformation appearing. Besides, with the groundwater in landslide body tending to stable, seepage force decreases because the hydraulic gradient becomes low, so the favorable effect declines. Therefore, the stability of strong deformation region is decreasing with reservoir water rising.

However, during reservoir water level descending, from the distribution of seepage field in Fig. 4b, it can be seen that the seepage force directs outside the landslide body. Its normal and tangential component forces on the slipping surface both decrease the antisliding force. Thus, under the combined action of uplift force and seepage force, the stability of strong deformation region dramatically decreases, especially at the initial stage of descending from the altitude of 173 m. The reason is that at the beginning of reservoir water descent, there is a lag of groundwater in the landslide body, so the hydraulic gradient is very large, and it is extremely unfavorable to the stability. Therefore, the stability is quite low at initial descending stage. From the stability analysis result in Fig. 3b, it can be seen that during reservoir water level descending from 173 to 170 m, the adverse effect of the seepage force is relatively eminent. However, with the continuous reservoir water level descending, for the good permeability of landslide body and slow descending rate of reservoir water level, the lag effect of groundwater in the landslide body gradually weakens, and consequently, the hydraulic gradient is reduced; thus, the seepage force decreases, and its adverse effect on the stability becomes low. In Fig. 3b, it can be seen that after reservoir water level descends to the altitude of 170 m, the detrimental effect of seepage force is not obvious. However, generally speaking, the stability of strong deformation region improves with the descending reservoir water.

From the analysis above, it can be drawn that because the permeability of Hefeng landslide is relatively good, during reservoir water rising, the favorable effect of seepage force weakens the unfavorable effect of uplift force, so rising of the reservoir water has little effect on the stability, and no deformation is caused, but during reservoir water descending, the unfavorable effect of seepage force superimposes the unfavorable effect of uplift force, which makes the stability dramatically decrease and leads to the failure of the accumulation body in front of the landslide.

## CONCLUSIONS

(1) The accumulation body of old landslide provides the internal condition of the landslide body, sliding zone, sliding bed, and activity place of groundwater for the deformation.

(2) Strong deformation occurs in the middle of Hefeng landslide during reservoir water descending. Shear fractures distribute in the front of strong deformation region and tension fractures are in the back. The time of fissure appearing closely corresponds to the time of reservoir water fluctuation.

(3) The action of hydrostatic pressure of reservoir water is equivalent to the action of uplift force and seepage force for the landslide body below the phreatic line during the rising and descending processes of reservoir water level. Uplift force is unfavorable to the stability. Seepage force is favorable to the stability during reservoir water level rising, but it is unfavorable during reservoir water level descending. Therefore, under the combination action of both forces, reservoir water rising has few effect on the stability, while reservoir water descending makes the stability dramatically decrease.

In summary, reservoir water level fluctuation is the main inducement factor of the deformation of He-

feng landslide. For relatively permeable reservoir landslide, rising of reservoir water has little effect on the deformation, but the drawdown of the water will dramatically decrease the stability and lead to the failure of the accumulation body in front of landslide.

**REFERENCES CITED**

Fu, H. Y., Liu, X. X., Li, Q. M., 2008. Research on Landslide Stability by Sudden Drawdown of Reservoir Level. *Progress in Safety Science and Technology*, 7: 2188–2191

Jian, W. X., Wang, Z. J., Yin, K. L., 2009. Mechanism of the Anlesi Landslide in the Three Gorges Reservoir, China. *Engineering Geology*, 108(1–2): 86–95

Li, M. C., Wang, Z. Y., Liu, J., 2008. 3D Evaluation and Analysis of Landslide Instability Mechanism of Reservoir Banks: A Case Study in the Three Gorges Reservoir. *International Symposium on Computer Science and Computational Technology*, 1: 560–563

Li, S. J., Knappett, J., Feng, X. T., 2009. Investigation of Slope Stability Influenced by Change of Reservoir Water Level in Three Gorges of China. In: Flow in Porous Media—From Phenomena to Engineering and Beyond. International Forum on Porous How and Application, Wuhan. 911–916

Li, D. Y., Yin, K. L., Leo, C., 2010. Analysis of Baishuihe Landslide Influenced by the Effects of Reservoir Water and Rainfall. *Environmental Earth Sciences*, 60(4): 677–687

Liu, Y. W., Chen, H. X., Liu, Q. Q., et al., 2005. Experimental Study on Pore Pressure in Rock-Soil Slope during Reservoir Water Level Fluctuation. *Science in China* (*Series E*), 48(S): 196–208

Lu, T. H., 2002. Mechanics of Soil. Hohai University Press, Nanjing. 238 (in Chinese)

Song, K., Yan, E. H., Li, J., 2008. The Response Research of Groundwater in Bedding Bank Slope of Decline of the Reservoir Water. *Proceedings of First International Conference of Modelling and Simulation*, 6: 99–104

Wang, L. X., Ma, J. H., Bian, Z. H., et al., 2005. Reservior and Slide Control Techniques. Yangtze River Press, Wuhan. 228 (in Chinese)

Wang, M. H., Li, X. P., Yan, E. C., 2007. A Study on Numerical Simulation of Stability and Failure Mode of a Reservoir Landslide. *Water-Rock Interaction*, 1–2: 1417–1419

Yao, A. J., Heng, C. Y., Zhang, Z. M., et al., 2008. Typical Harbor Bank Slopes in the Three Gorges Reservoir: Landslide and Collapse and Their Stability Control. *Landslides and Engineered Slopes: From the Past to the Future*, 1–2: 1825–1829

Yin, Y. P., Wang, H. D., Gao, Y. L., et al., 2010. Real-Time Monitoring and Early Warning of Landslides at Relocated Wushan Town, the Three Gorges Reservoir, China. *Landslides*, 7(3): 339–349

Zhang, J. F., Li, Z. G., Qi, T., 2005. Mechanism Analysis of Landslide of a Layered Slope Induced by Drawdown of Water Level. *Science in China* (*Series E*), 48(S): 136–145

Zhang, Z. H., Yao, H. Y., Ye, F., 2009. Study on the Selection of Deformation Monitoring Profiles of Landslides Induced by the Fluctuation of Water Level of Three Gorges Reservoir. In: Flow in Porous Media—From Phenomena to Engineering and Beyond. International Forum on Porous Flow and Application, Wuhan. 906–910

Zhu, D. L., Ren, G. M., Nie, D. X., et al., 2002. Effect and Forecasting of Landslide Stability with the Change of Reservoir Water Level. *Hydrogeology and Engineering Geology*, (3): 6–9 (in Chinese with English Abstract)