Deformation characteristics and stability evolution behavior of Woshaxi landslide
during the initial impoundment period of the Three Gorges reservoir

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Abstract: The study area, Woshaxi landslide, is 400 m long and 700 m wide, with an average thickness of approximately 15 m and a volume of $4.2 \times 10^6 \text{ m}^3$. The Woshaxi landslide, which is located on the Qinggan River, a tributary of the Yangtze River in the Three Gorges reservoir area, is just 1.5 km from the Qianjiangping landslide. The Qianjiangping landslide following the Three Gorges reservoir impoundment was caused by the combined effects of rainfall and reservoir water level fluctuation. In this study, the Woshaxi landslide's deformation characteristics and mechanism are investigated based on deformation monitoring data and a geological survey during the initial impoundment period of the Three Gorges reservoir. Furthermore, based on the characteristics of the combined effects of reservoir water level fluctuation and rainfall in the Three Gorges reservoir area, the stability evolution behavior of the Woshaxi landslide during the initial impoundment period of the Three Gorges reservoir is investigated.

Keywords: Slope; Rainfall; Reservoir water level fluctuation; Landslide

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1. Introduction and problem description

Investigations on landslides in the Three Gorges reservoir area indicate that rainfall was the primary trigger of landslides in the reservoir area (Yin et al. 2012; Sun et al. 2016a, 2016b) before the reservoir impoundment of the Three Gorges. As construction of the Three Gorges project progressed and reservoir impoundment and normal operation subsequently began after project completion, reservoir water level fluctuations emerged as a further major trigger of reservoir bank slope landslides (Chen et al. 2003; Yin et al. 2012; Sun et al. 2016c). Therefore, rainfall and reservoir water level fluctuation are major external factors for some possible reactivation of ancient landslides in the Three Gorges reservoir area. In particular, the Qianjiangping landslide, the geological-structural context of which is similar with the Woshaxi Landslide, on July 13, 2003 after the Three Gorges reservoir impoundment (Wang et al. 2004, 2008; Yin et al. 2015) led to 14 deaths and 10 missing persons, which raised serious alarm. This landslide was 1,200 m long with a widest front edge of approximately 850 m, a maximum thickness of approximately 30 m, and a total volume of approximately $2.0 \times 10^7 \text{ m}^3$. After the landslide, many research results suggested that rainfall and reservoir water level fluctuations were major triggers (Xiao et al. 2010a, 2010b; Yin et al. 2015; Wang et al. 2016).

In the Three Gorges reservoir area, there are many landslides. These landslides may be reactivated by reservoir water level fluctuations. To ensure the stability of the reservoir bank slope during dispatch under normal reservoir water levels and to prevent a natural disaster, the Chinese government has invested large amounts of money. In surveys and design reviews of landslide projects in the Three Gorges reservoir area, there are some problems resulting from the following physical conditions that require clarification and solution: the phreatic line when the reservoir water level fluctuates or when rainfall occurs. Reservoir water decline is the most unfavorable factor for a slope and normally results in a landslide (Morelli et al. 2017). Reservoir water fluctuation and rainfall contribute to unstable seepage conditions, which are related to factors such as reservoir water fluctuation speed, slope

1 permeability coefficient, and rainfall (García-Aristizábal et al. 2012). The correct
2 approach is to determine the phreatic line based on all of these factors, then to
3 determine the permeability pressure based on the phreatic line and to perform stability
4 analysis. However, most survey organizations currently determine the phreatic line
5 based on the designer's experience. Basing the stability analysis on an arbitrarily
6 determined line may introduce risk factors into the management of the project. On the
7 other hand, how slope stability evolves under the combined effects of reservoir water
8 level fluctuations and rainfall is of vital importance for power generation and flood
9 discharge control at the Three Gorges reservoir area.

10 Phreatic line determination is a free-surface (unconfined) seepage problem in
11 geotechnical mechanics (Chen et al. 2008). For the free-surface seepage problem, the
12 critical element is to determine the free surface that delimits the flow boundaries via
13 nonlinear numerical techniques such as the finite difference method with adaptive
14 mesh (Cryer 1970) and the finite element method with adaptive mesh (e.g., Taylor and
15 Brown 1967; Finn 1967; Neuman and Witherspoon 1970) and fixed mesh (Baiocchi
16 1972; Bathe and Khoshgoftaar 1979; Kikuchi 1977; Alt 1980; Oden and Kikuchi 1980;
17 Friedman 1982; Desai and Li 1983; Baiocchi and Capelo 1984; Westbrook 1985).
18 Among all of the proposed methods, the "Extended Pressure" (EP) method, initially
19 proposed by Brezis et al. (1978) and based on the finite difference method, is one of
20 the simplest and most efficient methods. Through an extension of Darcy's law, the EP
21 method reduces variational inequalities to simpler equalities that are then applied to
22 the entire computational domain. Based on variational inequalities, Zheng et al. (2005)
23 and Chen et al. (2008) made contributions to the solution of the free-surface
24 (unconfined) seepage problem for slopes and dams. To improve the solution accuracy
25 and computational efficiency of the unconfined seepage problem via the EP method, a
26 reasonable selection is proposed by analyzing the error of finite difference equations
27 and their iteration schemes (Ji et al. 2005). Significant progress has been made in
28 determining the phreatic line for slopes, especially via numerical analysis methods
29 such as the finite difference and finite element methods. However, these numerical
30 methods are not widely used in engineering practice and are largely ignored in soil

mechanics textbooks, mainly because they involve complex derivations and implementation. Thus, a simple and efficient procedure is required for practical engineering, education and training.

In engineering practice, changes in groundwater management and slope stability are usually handled separately using an uncoupled approach (Dong et al. 2016; Mohammad et al. 2015). Specifically, the pore water pressure range of a slope caused by groundwater level variation is determined first. Then, the resulting pore water pressures at potential failure surface are used in a limit equilibrium analysis to assess slope stability conditions in terms of a Safety Factor (SF). Based on this analysis, Van Asch and Buma (1997) proposed a one-dimensional hydrological model to describe groundwater fluctuation versus rainfall and a limit equilibrium method to assess the temporal frequency of landslide instability. Conte and Troncone (2012a) developed a simplified infinite-slope-based method to assess slope stability and an analytical solution (Conte and Troncone 2008) to evaluate pore pressure variation on the slip surface from pressure measurements using a piezometer above the surface. However, the limit equilibrium method is inadequate for active landslide analysis whose aim is more of an accurate displacement prediction than a SF calculation. Prompted by this deficiency, Calvello et al. (2008) proposed that the displacement rate measured at a selected point on the slope should be related empirically to a SF calculated by the limit equilibrium method. On the basis of several analytical solutions, an approach was presented by Conte and Troncone (2012b), which combines a simple infiltration model for calculating slope rain infiltration induced pore water pressure variation with a sliding-block model for assessing whether a slope failure is caused by a recorded rainfall.

Based on deformation monitoring data and a geological survey of the Woshaxi landslide during the initial impoundment period of the Three Gorges reservoir, the deformation characteristics and mechanism of the Woshaxi landslide are investigated in this study. Furthermore, based on the combined effects of reservoir water level fluctuations in the Three Gorges reservoir area and rainfall, a method is proposed to calculate the effects of reservoir water level fluctuation and rainfall on the phreatic

line along a slope. Based on this method, a Woshaxi landslide stability evolution mechanism during the initial impoundment period of the Three Gorges reservoir is established. An outline of the research procedure of this project is shown in Fig. 1.

2. Study area

The Woshaxi landslide, which is located on the Qinggan River, a tributary of the Yangtze River in the Three Gorges reservoir area, is just 1.5 km from the Qianjiangping landslide. The landslide is 400 m long and 700 m wide, with an average thickness of approximately 15 m and a volume of $4.2 \times 10^6 \text{ m}^3$. Therefore, research on the deformation mechanism of the Woshaxi landslide is of great importance to the prevention of ancient landslides in the Three Gorges reservoir area.

The Woshaxi landslide is located at the right bank of the Qinggan River, the high-lying south-west, north-eastern low in topography. The elevation of its trailing edge is about 405 m, and that of its toe is about 140 m. The Qinggan River flows up its toe from the west to the east side of the landslide. The landslide is approximately 6 km from the river mouth, approximately 1.5 km from the Qianjiangping landslide at the left bank of the Qinggan River, and 50 km from the Three Gorges Dam. The geographical location is shown in Fig. 2.

On February 24, 2007, in the middle of the landslide front edge, a secondary landslide with significant slip deformation occurred, which is a partial reactivation. The trailing edge of the secondary landslide is located at a rural highway, the elevation of which is approximately 225 m. The elevation of its toe is below 152 m (water level on March 10, 2007). Its geometries are shown in Fig. 3. Its plane area is approximately $3.3 \times 10^4 \text{ m}^2$, and its total volume is approximately $5.0 \times 10^5 \text{ m}^3$. A landslide overview and the secondary landslide are shown in Figures 3-4.

3. Composition and structural feature of landslide area

(1) Landslide materials: The Woshaxi landslide mass consists primarily of soil-rock-mixture including some rock block and residual slope soil from the Holocene epoch. The soil composition is clay with sandstone and mudstone, whose

1 color is purple red mixed with gray or drab, whose consistency varies from
2 moderately dense to loose. However, primary rock block composition is 30~50%
3 sandstone and mudstone with sharp edges or dull edges, whose diameters are
4 normally 1~15 cm and up to 50 cm. They are piled randomly and have varying sizes.
5 Based on the survey data, the thickness of this landslide is normally 10~30 m from the
6 trailing edge to the front edge and the thickest part at the front edge is 50m.

7 (2) Bedrock: The overall rock occurrence is $100^{\circ} \angle 25^{\circ}$; the orientation
8 intersects with the overall bank slope orientation at a large angle, and it belongs to the
9 oblique structure bank slope. Three groups of fractures develop inside the rock, whose
10 occurrences are $155^{\circ} \sim 160^{\circ} \angle 75^{\circ} \sim 85^{\circ}$, $210^{\circ} \sim 225^{\circ} \angle 60^{\circ} \sim 70^{\circ}$, and $20^{\circ} \sim 40^{\circ} \angle 65^{\circ} \sim 70^{\circ}$,
11 respectively.

12 (3) Hydrogeological condition of the landslide. The Qinggan River, which is a
13 tributary of the Yangtze River in the Three Gorges reservoir area, flows through the
14 slope toe. The water level varies from 145~175 m (a.s.l.). The front edge slope (20~50
15 m) is submerged, and the river water erodes and empties the landslide slope bottom.
16 Thus the reservoir water and landslide groundwater supplement each other because of
17 reservoir water level fluctuation. Additionally, two small ditches exist in the landslide,
18 which store water in the rainy season, dry up in the dry season, and replenish
19 landslide groundwater. The landslide is also supplied by rainfall. Groundwater in the
20 landslide area primarily takes the form of loose pore water and bedrock fracture water.
21 For the pore water in the loose accumulation layer, the water-bearing medium is a
22 landslide deposit with weak permeability, permeability coefficient of which is
23 $K=5.00 \times 10^{-4} \sim 7.80 \times 10^{-5}$ cm/s. Therefore, pore water has a better occurrence condition.
24 The landslide shallow surface is primarily arable land (cornfield) with loose structure
25 and good permeability whose permeability coefficient is $K=1.00 \times 10^{-3} \sim 5.80 \times 10^{-3}$ cm/s.
26 That condition is favorable for underground water infiltration, movement and
27 discharge. The landslide zone soil is clay soil with gravel, is moderately dense~dense
28 with weak-moderate permeability, and has a permeability coefficient of
29 $K=1.20 \times 10^{-4} \sim 8.50 \times 10^{-5}$ cm/s. Groundwater in the landslide area is supplied primarily
30 by rainfall and reservoir water backflow to the landslide caused by increases in

reservoir water; it may also originate from manual irrigation water used on arable land. Because the landslide is located at the slope bottom of the Qinggan River valley, groundwater is locally supplied and locally discharged; the Qinggan River water level is the discharge base level and features the lowest groundwater level in the landslide area.

4. Landslide deformation characteristics and root cause analysis

4.1 GPS monitoring

Seven GPS monitoring points, including ZG356~ZG359 and WSX-1~WSX-3, are deployed in the Woshaxi landslide area. In this study, real-time translocation mode was employed and its time accuracy is 0.2 second. Among them, 3 monitoring points are in the secondary landslide with significant deformation (WSX-1, WSX-2, WSX-3) and are distributed along the same longitudinal section. This monitoring point distribution is shown in Fig. 4. However, the WSX-2 and WSX-3 measurement points were submerged because of the Three Gorges reservoir impoundment. GPS monitoring results from the start of professional monitoring in September 2006 to its end in December 2009 are shown in Table 1.

Monitoring results indicate that the accumulated displacement measurements of 4 GPS monitoring points (ZG356~ZG359) previously deployed in the Woshaxi landslide varied moderately within a limited range. This variation was caused by monitoring error; the 4 measurement points had no significant displacement.

However, displacements at 3 monitoring points in the secondary deformation body, which is located at the middle and lower parts of the Woshaxi landslide, experienced significant variation from the start of professional monitoring on April 17, 2007 to its end in December 2009, as shown in Fig. 5 and Table 1.

The secondary landslide's vertical deformation demonstrated essentially the same trend as the horizontal deformation (Fig. 5). Fig. 6 shows the relationship between accumulated displacement of the secondary landslide (at the WSX-1 and

WSX-2) and the monthly rainfall and reservoir water levels. This diagram indicates that secondary landslide displacement is closely related to reservoir water level fluctuations. In middle and late April 2007, decreases in the reservoir water level resulted in the rapid growth of landslide slope deformation. Subsequently, as the reservoir water level stabilized, landslide deformation gradually stabilized. However, at the end of August 2007, the reservoir water level continued to rise, whereas landslide deformation gradually stabilized. At the end of April 2008, the reservoir water level dropped again from 156 m to 145 m (a.s.l.), which triggered rapid landslide slope deformation. Until the middle of June, the reservoir water level was essentially stable and landslide deformation gradually stabilized. The above analysis indicates that decreases in reservoir water level had a significant impact on landslide deformation. It also indicates that the secondary landslide deformation response was delayed relative to the reservoir water level variation time.

Rainfall also has some influence over secondary landslide deformation. The diagram shows that the landslide deformation underwent an abrupt change at the end of April each year as the reservoir area entered the rainy season in April or May and the rainfall increased. Therefore, under the combined effects of reservoir water level decline and flood season rainfall in April of each year, landslide deformation grew rapidly.

4.2 Field survey and deformations evolution

From the end of February to the middle of March 2007, substantial slip deformation occurred at the middle of the Woshaxi landslide's front edge, and a secondary landslide occurred. A crack at the trailing edge of the deformation area took the form of sinking deformation, in which the sink was more severe than the horizontal crack. The sink was 15~45 cm. And the crack was 10~20 cm wide and 25 m long with orientation of $290^{\circ}\sim 308^{\circ}$. The crack exhibited fully developed penetration, which damaged the village traffic way (Fig. 7(a)). At the northwest side of the deformation area, along the $320^{\circ}\sim 68^{\circ}$ direction emerged a discontinuous feather-shaped tensile crack, which cut off the lower part (Fig. 7(b)) of the village traffic way (Fig. 7(a)) and caused the road surface to collapse to the Qinggan River at the slope bottom. The crack was 5~20 cm wide, the sink was 10~30 cm wide. At the southeast boundary of

1 the deformation area, along the $60^{\circ}\sim 85^{\circ}$ direction emerged a feather-shaped crack
2 with fully developed penetration (the orientation for part of the feather-shaped crack
3 was 95°), which extended to the Qinggan River at the slope bottom. The crack was
4 5~20 cm wide; the sink was 10~30 cm wide. There were signs of newly developed
5 tensile crack deformation (Fig. 7(c)).

6 In early April of 2007, the deformation at the front edge of the middle Woshaxi
7 landslide increased and an arc tensile crack was formed. The crack was 6~15 cm wide,
8 the vertical base was 50 cm. By the end of April, a 500 m long arc crack at the trailing
9 edge of the secondary landslide had already developed into a penetration. The
10 elevation of this secondary landslide trailing edge was approximately 220 m; the front
11 edge was under the 156 m (a.s.l.), which is reservoir water level line. In the secondary
12 landslide area, the crack was well developed, with an extended length of 50-100 m
13 and a width of 10~50 cm. A 50~100 cm high crack lower base banquette was
14 observed in several places. From the deformation failure area trailing edge to the front
15 edge at the Qinggan River, the horizontal crack distribution was dense; the soil in the
16 area was loose and was cut by the crack into multiple blocks. The left hand crack
17 orientation was $310\sim 320^{\circ}$, and the maximum lower base was 120 cm, which extended
18 upward to the arc crack at the trailing edge and downward to the Qinggan River side.
19 The right side crack orientation was $50\sim 60^{\circ}$, and the maximum lower base was 100
20 cm, which extended upward to the arc crack at the trailing edge and downward to the
21 Qinggan River side. A chair-shaped crack formed along the approximate path of the
22 landslide.

23 In June 2007, landslide deformation slowed down considerably; most original
24 crack had no notable macro deformation, whereas some cracks exhibited signs of
25 new openings. In July 2007, the crack at the trailing edge of the deformation area
26 continued to exert tension on the lower base; the crack deformation at the slope and
27 trailing edge worsened. The traffic way (which was repaired and filled in early April)
28 was displaced by the crack; lower base deformation occurred again. The crack was
29 5~20 cm wide; the vertical lower base was 70 cm. The village traffic way was
30 damaged again. Outside the Woshaxi landslide secondary landslide area, no other
31 significant surface deformation was observed. After August 2007, the Woshaxi

1 landslide and middle area with severe deformation exhibited no other notable sign of
2 surface deformation.

3 From May 4, 2008, the secondary landslide boundary arc crack at the middle of
4 the Woshaxi landslide experienced notable tensile deformation in the direction of the
5 original cracks. The new tensile lower base was approximately 30 cm and had already
6 grown into penetrations. Cracks grew in the secondary landslide area; these had an
7 extended length of 70~100 m and were mostly in arc form. The new crack had an
8 expanded width of 10~30 cm. New expanded lower base banquettes (10~20 cm high)
9 were observed in multiple locations. From the deformation failure area trailing edge
10 to the front edge at the Qinggan River side, the horizontal crack distribution was
11 dense. In this area, the soil was loose and cut by the crack into multiple blocks. On
12 May 19, 2008, the traffic way that was repaired and filled multiple times in 2007 was
13 displaced by the crack; lower base deformation occurred again. The crack was 5~15
14 cm wide, and the vertical lower base was 30 cm; the village traffic way was damaged
15 again. The left hand crack orientation was 300-310°, and the maximum newly formed
16 lower base was 30 cm, which extended upward to the trailing edge arc crack and
17 downward to the Qinggan River side. The right side crack orientation was 30-50°, and
18 the maximum newly formed lower base was 40 cm, which extended upward to the
19 trailing edge arc crack and downward discontinuously to the Qinggan River side. A
20 chair-shaped crack formed along the approximate path of the landslide. On May 24,
21 2008, the traffic way edge at the right rear side of the landslide displayed a tensile
22 crack 10~20 cm wide and 30~50 cm deep; the traffic way at the landslide trailing
23 edge continued to sink (Fig. 7(d)). The landslide front edge left side collapsed (Fig.
24 7(e)). At the landslide front edge, groundwater exited the soil in the form of a stream.
25 On May 26, 2008, in the traffic way at the landslide right rear side, two conspicuous
26 cracks emerged whose length was 3~5 m and whose width was 1~3 cm. The original
27 cracks at the traffic way edge continued to expand, and their width increased to 30~50
28 cm and depth to 50~100 cm. The traffic way, which was repaired in the afternoon of
29 May 25, was damaged again by a landslide. The telegraph pole in the middle of the
30 landslide exhibited a more severe tilt (Fig. 7(f)). The landslide left side continued to
31 slide and collapse, which was accompanied by groundwater emerging from the

1 landslide boundary. On May 27, the original crack in the landslide continued to
2 expand; the telegraph pole at the middle of the landslide fell down at 8:28 am. Outside
3 the Woshaxi landslide secondary landslide area, there was no clear sign of surface
4 deformation. After June 2008, the Woshaxi landslide secondary landslide deformation
5 gradually stabilized and there was no other notable sign of surface deformation.

6 Since May 14, 2009, the secondary landslide arc crack at the middle of the
7 Woshaxi landslide exhibited notable tensile deformation that followed the path of the
8 original crack. At the left rear side, three new tensile lower base cracks formed; the
9 maximum lower base was approximately 35 cm. At the left rear side, two new tensile
10 lower base cracks formed; the maximum lower base was approximately 50 cm.
11 Cracks on both sides grew into penetrations. Cracks grew in the secondary landslide
12 area; these had an extended length of 50-80 m and were mostly in arc form. The new
13 crack tensile width was 10-30 cm, and the soil at the middle rear slope was cut off.
14 From the trailing edge of the deformation failure area to the front edge of the Qinggan
15 River side, the horizontal crack distribution was dense. The soil in the area was loose
16 and was cut by the crack into multiple blocks. On May 27, 2009, the traffic way
17 repaired and filled multiple times in 2008 was displaced by the crack; lower base
18 deformation occurred again. The crack was 5~15 cm wide, and the vertical lower base
19 was 25 cm; the village traffic way was damaged again. The left side crack orientation
20 was 300~310°, and the maximum newly formed lower base was 30 cm, which
21 extended upward to the trailing edge arc and downward to the Qinggan River side.
22 The right side crack orientation was 30~50°, and the maximum newly formed lower
23 base was 50 cm, which extended upward to the trailing edge arc crack and downward
24 discontinuously to the Qinggan River side. A chair-shaped crack formed along the
25 approximate path of the landslide. After June 2009, signs of secondary landslide
26 surface deformation decreased significantly.

27 These observations indicate that the Woshaxi secondary landslide formed in
28 March 2007 because of reservoir water level decline. With the continuous decline in
29 reservoir water level and increase in rainfall during the flood and rainy season,
30 secondary landslide deformation grew continuously. After August 2007, as rainfall
31 decreased, the Woshaxi secondary landslide deformation gradually stabilized. In May

2008, when the reservoir water level fell from 156 m to 145 m (a.s.l.) and rainfall increased during the flood and rainy season, secondary landslide deformation grew rapidly. When the reservoir water level gradually stabilized and rainfall decreased, the Woshaxi secondary landslide deformation again gradually stabilized. After May 2009, when the reservoir water level dropped and rainfall increased during the flood and rainy season, secondary landslide deformation again grew rapidly. After July, the secondary landslide deformation again gradually stabilized.

4.3 Influencing factors of landslide deformation

Based on the deformation monitoring and macroscopic geological survey analyses, the major factors affect landslide deformation are:

(1) Reservoir water level decline. Landslide displacement is closely related to reservoir water level fluctuation. When the reservoir water level dropped, the groundwater level along the natural slope dropped accordingly. However, the groundwater level on the slope dropped at a much lower speed than the reservoir water level, which led to a significant increase in the hydraulic gradient and hydrodynamic pressure for the groundwater level along the slope. At that time, most of the slope was still in the saturated state with a relatively heavy weight. This trigger led to a rapid decline in slope stability. When the reservoir water level essentially stabilized, landslide deformation gradually stabilized. Therefore, the reservoir water level decline had a significant impact on landslide deformation. Additionally, the Woshaxi landslide deformation response was delayed relative to the reservoir water level variation time.

(2) Rainfall. Rainfall raised the groundwater level and increased the landslide ground hydraulic gradient. Moreover, a high volume of rainfall infiltrated the landslide surface and had a softening effect on the landslide composition and landslide zone soil. This directly reduced the landslide zone soil's shear strength, which may have even resulted in a complete loss of mechanical stability. The groundwater static hydro-pressure effect also increased the landslide weight. Additionally, the groundwater hydrodynamic pressure effect increased slip along the seepage direction. The increase in landslide dynamic and static hydro-pressure and the

groundwater's saturation and softening effect on the landslide zone soil rendered the landslide prone to deformation and instability.

(3) Formation lithology. The landslide mass is soil-rock mixture, composition consists of which is rubble and soil with loose structure. The landslide is likely to undergo deformation under an external force and thus provides the material condition for landslide deformation. The landslide zone material consists primarily of rubble and soil in an accumulation layer and an underlying bedrock contact zone. The slide bed is Jurassic feldspar quartz sandstone with a small percentage of mudstone belonging to a slippery formation. The rock occurrence is $100^{\circ} \angle 25^{\circ}$; the slope is oblique. All of these factors facilitate the forward slip of overlying landslide material.

(4) Topography. The landslide left and right boundaries meet at a junction of bedrock ridge and valley whose overall gradient is 20° . This unique topography meets the spatial requirement for a landslide.

The Woshaxi secondary landslide underwent significant deformation when the reservoir water level dropped and rainfall was abundant. This finding indicates that reservoir water level decline and rainfall have a substantial impact on landslide stability. Formation lithology and topography are the basic material conditions of the landslide.

5. Stability evolution law

5.1 Analytical techniques overview

Among various strict slice methods that are classified as conventional limit equilibrium methods, the normal pressure on the slice bottom is eliminated by two equilibrium equations for a single slice; next, uncertain factors are applied to the inter-slice force (Bishop 1955). In this way, the static indeterminate problem of the ultimate slope SF is solved. Examples include the Morgenstern-Price method (Morgenstern and Price1965), Spencer's method (Spencer1967), the Swedish method (Fellenius1936), the Bishop simplified method (Bishop1955), and the Janbu simplified method (Janbu1937). Numerous studies on these slice methods have

1 demonstrated the importance of the inter-slice force assumption in solving the slope
2 stability problem (static indeterminate problem) (Bell1968). These conventional slice
3 methods are known as local analysis methods. Correspondingly, another class of
4 methods are called global analysis methods; these include the graphic method (Sarma
5 1932), variation method (Baker 2005), and Bell global analysis method (Bell 1968).
6 Different from other limit equilibrium methods, the Bell method treats the entire
7 landslide rather than a single slice as the study object, which requires no introduction
8 of inter-slice force and provides a new approach to implement the strict slice method.
9 Theoretically, the landslide surface normal stress distribution assumption in the global
10 method should be easier to understand than the inter-slice resultant force direction
11 distribution assumption in the Morgenstern-Price method; however, this method has
12 never gained much attention. Even in a comprehensive review of limit equilibrium
13 methods by Duncan (1996), Bell's work was not mentioned. It was not until 2002 that
14 similar methods caught the attention of researchers (Zhu et al. 2002, 2005; Zheng and
15 Tham 2009). Similar to the deduction process in the Bell method, Zhu et al. (2002,
16 2005) employed quadratic interpolation to approximate the normal stress distribution
17 on the landslide surface and finally derived a unitary cubic equation whose unknown
18 quantity was the SF. In another publication, Zheng and Tham (2009) proposed the
19 global analysis method, and Green's formula was employed to convert relevant
20 domain integration into boundary integration without slicing the landslide. In this way,
21 global limit equilibrium analysis of landslide was realized.

22 **5.2 Stability analysis methodology**

23 However, during an engineering survey and design review of Three Gorges reservoir
24 area landslides (a typical example is the Woshaxi landslide), some problems were
25 identified that need to be solved: (1) Lack of evidence to determine the phreatic line
26 under the condition of fluctuating reservoir water level. (2) Lack of rigor in
27 determining the phreatic line under the condition of rainfall. Sun et al. (2017)
28 proposed a method to calculate the slope phreatic line under the combined effects of
29 reservoir water level fluctuation and rainfall. In this article, phreatic line variation
30 caused by the reservoir water level fluctuation and raining and the details of slope

stability analysis can be seen in Sun et al. (2017).

5.3 Stability evolution behavior

The reservoir water level variation curve for the initial impoundment period of the Three Gorges reservoir and the average monthly rainfall during this period is shown in Fig. 6. Based on such calculation conditions, the stability evolution mechanism of the Woshaxi secondary landslide (the section is shown in Fig. 4) during this period is investigated. Physical parameters are listed in Table 2. In the table, three parameters that affect the slope phreatic line (permeability coefficient, porosity and saturation) are calculated; the effects of these parameters on the SFs are analyzed. In this study, SFs for each group of parameters in Table 2 under three conditions, including reservoir water level variation alone, rainfall alone and the combined effects of rainfall and reservoir water level fluctuation are calculated (Figures 8-10).

The SFs of Woshaxi landslide vary with reservoir water level fluctuation under condition of reservoir water level fluctuation only or the condition of rainfall only, have been exhibited in Sun et al., 2017. From the former condition, the SF increases with the reservoir water level rises. The reason is that as the reservoir water level rises, the slope bottom pressure increases, the slope hydro-pressure increases, and the hydrodynamic pressure points toward the slope interior. All these are factors that improve slope stability. The SF reduces as the reservoir water level declines homoplastically. Both of the slope bottom pressure and the slope hydro-pressure decrease with the reservoir water level decline. Thus the hydrodynamic pressure points toward the slope exterior and forms a pulling force. All these are factors unfavorable for slope stability. On the other hand, the SF from rainfall only is significantly lower than that from the fluctuation of reservoir water level only from the later condition. The SF varies with monthly rainfall variation. The trend indicates that a higher volume of rainfall results in a lower SF, and vice versa. This finding occurs because an increase in rainfall results in an increase in the phreatic line along the slope, which subsequently increases the hydrodynamic pressure and lowers the SF.

The stability evolution behavior of the Woshaxi landslide under the combined effects of reservoir water level fluctuation and rainfall during the initial impoundment

1 period are shown in Figures 8-10. The above results indicates that the reservoir water
2 level decline and rainfall increase result in a lower slope SF; however, a reservoir
3 water level rise and rainfall decline lead to a higher slope SFs. Under the combined
4 effects of reservoir water level fluctuation and rainfall, if the reservoir water level
5 declines and rainfall increases simultaneously, the slope stability declines. As shown
6 for April ~ May 2007-2009 in Figures 8-10, the SFs exhibit a declining trend.
7 However, if the reservoir water level rises while rainfall decreases, the slope stability
8 improves. As shown for September ~ November 2007-2009 in Figures 8-10, the SFs
9 exhibit a rising trend. Therefore, to prevent geological disasters such as landslides in
10 the Three Gorges reservoir area, measures should be taken to prevent the abrupt drop
11 of the reservoir water level in the rainy season. Three parameters affecting the slope
12 phreatic line (permeability coefficient, porosity and saturation) are assigned various
13 values to analyze their impact on the SFs. The impact of rainfall alone or reservoir
14 water level fluctuations alone is the primary reference; the combined effects of
15 rainfall and reservoir water level fluctuations are a combination of the two.

16

17 6. Discussions

18 Slope stability is closely related to reservoir water level fluctuation. The groundwater
19 level along the natural slope dropped accordingly as the reservoir water level dropped.
20 However, the groundwater level on the slope dropped at a much lower speed than the
21 reservoir water level, which led to a significant increase in the hydraulic gradient and
22 hydrodynamic pressure for the groundwater level along the slope. At that time, most
23 of the slope was still in the saturated state with a relatively heavy weight. This trigger
24 led to a rapid decline in slope stability. When the reservoir water level essentially
25 stabilized, slope stability gradually stabilized. Therefore, the reservoir water level
26 decline had a significant impact on landslide deformation. Additionally, the Woshaxi
27 landslide stability response was delayed relative to the reservoir water level variation
28 time. On the other hand, rainfall raised the groundwater level and increased the
29 landslide ground hydraulic gradient. Moreover, a high volume of rainfall infiltrated

1 the landslide surface and had a softening effect on the landslide composition and
2 landslide zone soil. This directly reduced the landslide zone soil's shear strength,
3 which may have even resulted in a complete loss of mechanical stability. The
4 groundwater static hydro-pressure effect also increased the landslide weight.
5 Additionally, the groundwater hydrodynamic pressure effect increased slip along the
6 seepage direction. The increase in landslide dynamic and static hydro-pressure and the
7 groundwater's saturation and softening effect on the landslide zone soil rendered the
8 landslide prone to deformation and instability. The impact of rainfall alone or
9 reservoir water level fluctuations alone is the primary reference; the combined effects
10 of rainfall and reservoir water level fluctuations are a combination of the two.

11 In Figures 8-10, the relationship between accumulated displacement of the
12 secondary landslide (at the WSX-1 and WSX-2) and the SFs are also exhibited. This
13 diagram indicates that secondary landslide displacement is roughly related to SFs
14 fluctuations.

15 In middle and late April 2007, decreases in the reservoir water level resulted in
16 the rapid growth of landslide slope deformation. Subsequently, as the reservoir water
17 level stabilized, landslide deformation gradually stabilized and the SF are slightly
18 lower. However, at the end of August 2007, the reservoir water level continued to rise,
19 whereas landslide deformation gradually stabilized and its SFs were higher a bit. At
20 the end of April 2008, the reservoir water level dropped again from 156 m to 145 m
21 (a.s.l.), which triggered rapid landslide slope deformation and pulled down the SFs.
22 Until the middle of June 2008, the reservoir water level was essentially stable and
23 landslide deformation gradually stabilized and SFs gradually upraised. The above
24 analysis indicates that decreases in reservoir water level had a significant impact on
25 landslide deformation and SFs. It also indicates that the secondary landslide
26 deformation and stability response was delayed relative to the reservoir water level
27 variation time.

28 Rainfall also has some influence over secondary landslide deformation and SFs.
29 The diagram shows that the landslide deformation and SFs underwent an abrupt
30 change at the end of April each year as the reservoir area entered the rainy season in
31 April or May. Therefore, under the combined effects of reservoir water level decline

and flood season rainfall in April of each year, landslide deformation grew rapidly and SFs reduced accordingly.

Some other interesting conclusions can be got as follows: 1) the effects of permeability coefficient and porosity on the overall SFs are insignificant in the condition of reservoir water level fluctuations; 2) in the case of rainfall, the porosity of soil above the phreatic line has the more significant impact on the SFs than the permeability coefficient and saturation; 3) the combined effects of rainfall and reservoir water level fluctuations are two of the most principal factors for landslides.

7. Conclusions

The research results indicate that the Woshaxi landslide underwent significant deformation lower SFs when the reservoir water level dropped and rainfall was abundant. However, the landslide deformation gradually stabilized in other cases. Similar results are available in respect of stability.

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3

4 **Figure captions:**

5 Fig. 1 An outline of the research procedure of this project.

6 Fig. 2 Geographical location map of Woshaxi Slope in the Three Gorges reservoir.

7 Fig. 3 Woshaxi Slope overview (Contour line of Woshaxi Landslide; Moving area of Secondary
8 landslide; Positions of surface failure).

9 Fig. 4 (a) Contour map and monitoring points of Woshaxi Slope; (b) Cross-section A-A' of
10 Woshaxi secondary landslide.

11 Fig. 5 Horizontal and vertical displacements of GPS monitoring points in Woshaxi Slope.

12 Fig. 6 Displacements of GPS monitoring points in Woshaxi Slope, average monthly rainfall, and
13 reservoir water level from 2007 to 2009.

14 Fig. 7 Photos of Woshaxi secondary landslide in March 2007 and May 2008: (a) Slope rear; (b)
15 Northwest side; (c) Southeast side; (a) Slope rear; (b) Lower left slope; (c) Telegraph pole on
16 the central slope.

17 Fig. 8 Safety factors and displacements of Woshaxi secondary landslide under combined
18 conditions of reservoir water level fluctuation and rainfall from 2007 to 2009 (various
19 permeability coefficients).

20 Fig. 9 Safety factors and displacements of Woshaxi secondary landslide under combined
21 conditions of reservoir water level fluctuation and rainfall from 2007 to 2009 (various
22 porosity).

23 Fig. 10 Safety factors and displacements of Woshaxi secondary landslide under combined
24 conditions of reservoir water level fluctuation and rainfall from 2007 to 2009 (various
25 saturation).

26

27

Figure01

Figure02

Figure03

Figure04

Figure05

Figure06

Figure07

Figure08

Figure09

Figure10

Table 1 The deformation of the monitoring points (Fig. 4) in the Woshaxi secondary landslide.

Monitoring points		2006.9~2009.12	2008		2009	
		Accumulated displacements (mm)	Annual displacements (mm)	Average speeds (mm/month)	Annual displacements (mm)	Average speeds (mm/month)
ZG356		11.6	3.2	0.3	9.2	0.8
ZG357		15.5	3.6	0.3	3.8	0.3
ZG358		5.7	8.2	0.7	10.6	0.9
ZG359		17.1	10.4	0.9	6.2	0.5
WSX-1	Horizontal	12298.3	5408.3	450.7	5151.8	429.3
	Vertical	-6269.0	-2726.0	227.2	-2511.0	209.3
Notes		ZG356~ZG359 from Sep. 2006.9; WSX-1 from 17 April 2007				

Table 2 Parameters of Woshaxi Slope

Weight unit γ (KN/m ³)		Shear strength				Unconfined aquifer thickness H_m (m)	Permeability coefficient K (m/day)	Porosity n	Degree of saturation Sr
Saturated condition	Natural condition	Saturated condition		Natural condition					
		c_e (kPa)	φ ($^{\circ}$)	c_e (kPa)	φ ($^{\circ}$)				
22.8	20.8	19.0	15.0	21.0	20.0	45.0	0.01/0.10/1.00	0.3	0.8
							0.1	0.1/0.3/0.5	0.8
							0.1	0.3	0.4/0.6/0.8