Chapter 9
Evaluation of the Roles of Reservoir Impoundment and Rainfall for the Qianjiangping Landslide in Zigui County, Three Gorges Area

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Abstract The Qianjiangping landslide occurred following the first impoundment of the Three Gorges reservoir and a prolonged rainfall. To evaluate the quantitative effects of the reservoir impoundment and rainfall on the landslide, a sensitive analysis was performed with particular consideration to the landslide's unique characteristics and the seven parameters susceptible to the interactions between the landslide's materials and water from the two sources. These parameters include unit weight of the landslide's material, groundwater level above the slip zone, shear strength components of the upper and lower sections of the landslide's slip zone, and uplift pressure of the reservoir water. Results of this study show that the factor of safety (FS) of the landslide was the most sensitive to the cohesion of shear strength of the slip zone's lower section, and the least sensitive to groundwater level above the slip zone. It is found that the effect of shear strength reduction of the slip zone's lower section was the most crucial in the landslide's initiation. The landslide resulted from the combined influences of the reservoir impoundment and rainfall. The role of the reservoir impoundment in the landslide was dominant with a contribution percentage about 61.3%, whereas rainfall may have been the factor triggering the landslide.

Keywords Qianjiangping landslide · Rise of reservoir water level · Prolonged rainfall · Sensitive analysis

Introduction

The sudden occurrence of the Qianjiangping landslide in Zigui county, the Three Gorges area, at 0:20 AM, July 14, 2003 not only caused 24 casualties and huge economic losses but also drew great attention from both the public and researchers. This landslide took place 43 days after the impoundment of the Three Gorges reservoir, and a prolonged rainfall of 162.7 mm during the period between June 21, 2003

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and July 11, 2003. Apparently, both the reservoir impoundment and the prolonged rainfall must have played important roles in the occurrence of this landslide. A number of researchers, e.g., Dai et al. (2004), Wang et al. (2004), Yang et al. (2006), believed that this landslide's occurrence was largely due to shear strength reduction of a pre-existing weak zone along a bedding plane of shale that was saturated by groundwater from both the reservoir impoundment and rainfall. Liu et al. (2005) argued that the influence of the reservoir impoundment on the landslide became significant only after the rise of the reservoir water level was greater than 15 m. Yin and Peng (2007) thought that the influence of rainfall on the landslide was greater than the reservoir impoundment because the shear strength of the landslide's slip zone had little change, as it was a pre-existing shear zone. Xiao et al. (2007) presented a result that the reservoir impoundment had a greater effect on the landslide's occurrence than rainfall. Obviously, there has been an argument about the relative importance of the reservoir impoundment and rainfall in the landslide's occurrence among researchers, and few studies show insightful understanding about the quantitative roles of the two effects on the landslide in terms of the interactions between the landslide's materials and water from the two sources.

It has been well recognized that water within a landslide decreases its stability in several ways as a result of a series of complex physical, chemical, and mechanical interactions between the landslide's materials and water. The most common processes include increasing unit weight of the landslide's materials, pore-water pressure at the slip zone, and seepage force within the landslide; reducing shear strength of its slip zone, etc. Thus, an in-depth understanding of water influence on a landslide should consider changes in all of the processes above. Certainly, decrease of a landslide's stability due to water influence mentioned is site-specific, because there is a great variation in landslide characteristics and nature of the water occurring within the landslides. For the Qianjiangping landslide, the reservoir impoundment mainly influenced its lower part, while rainfall infiltration should have mainly influenced its upper part above the reservoir water level. In this chapter, quantitative roles of the reservoir impoundment and rainfall in the Qianjiangping landslide were evaluated on the basis of a sensitive analysis of the factor of safety (FS) of the landslide with a series of parameters susceptible to the interactions between the landslide's materials and water from the two sources. Selection of the parameters was focused on the unique characteristics of the Qianjiangping landslide and nature of water from the two sources.

Site Description

The Qianjiangping landslide is located on the left bank of the Qingganhe River, one of the tributaries of the Yangtze River, where water level rose from 95 m above sea level (A.S.L) to 135 m after impoundment of the Three Gorges reservoir. At 0:20 AM, July 13, 2003, the slope of the river bank, about 20,000,000 m^3 in volume, rapidly slipped down about 200 m in less than 5 min and blocked the

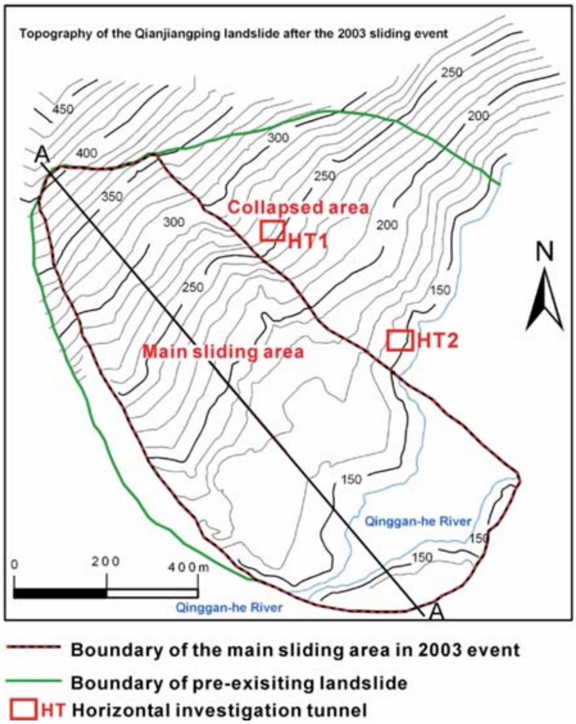

Fig. 9.1 Simplified plan of the Qianjiangping landslide (from Wang et al. 2008)

Qingganhe River, forming a landslide dam (Figs. 9.1 and 9.2). Field investigation post-landsliding found that the main scarp of the landslide was along the bedding plane of shale of early and middle Jurassic in age, and that the toe of its slip surface was located near the floodplain of the Qingganhe River, where the elevation was about 100–110 m A.S.L.

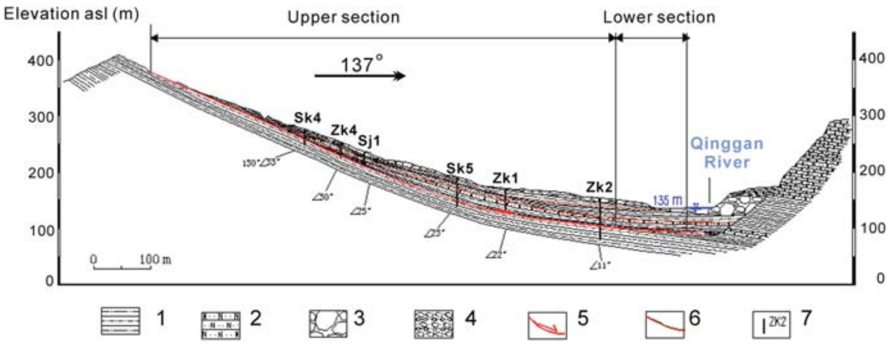

Fig. 9.2 Main cross section through the Qianjiangping landslide.
1: Silty mudstone + clayey siltstone; 2: Sandstone; 3: Colluvium; 4: Alluvium; 5: Main slip zone; 6: Sub-slip zone; 7: Borehole and its number (Please note that SJ1 denotes a deep shaft)

The landslide material was composed of loose to very loose colluvium, and highly fractured sandstone, siltstone, and mudstone of early and middle Jurassic age. The thickness of the colluvium was about 5–15 m, and that of the highly fractured classical rocks was 20–45 m. Field investigation and deep shaft results revealed that the sequence of the fractured classical rocks experienced no change compared with the intact bedrock, showing that their bedding planes had a dip of 32–15° downward and about parallel to the slope. In situ measurement using an in situ bulk density test showed that unit weight of the landslide's material varied, with a range of 16.05–22.57 kN/m^3 with an average value of 17.58 kN/m^3.

Eight boreholes and two deep shafts disclosed that the landslide had a main slip zone and two to three sub-zones. The sub-zones were found to be the pre-existing tectonic shear zones developed along bedding planes of mudstone and siltstone. Prominently, the main slip zone consisted of two distinctive sections characterized by their occurrences and locations: the upper and lower sections (Fig. 9.2).

The upper section of the main slip zone, containing a striated and slickensided surface, was seen to develop along the bedding plane of the dark gray shale interbedded by the mudstone and sandstone. Occurrence of this section of the slip zone was found to be consistent with its underlying bedrock, showing an "L" shape occurrence with dip angle 32° at the main scarp and 15° near the middle part of the slope. Wen (2008) found that this part of the slip zone was a pre-existing shear zone that resulted from tectonic shearing and argillation of shale due to progressive weathering. The slip zone, about 5–10 cm thick, very soft and very wet, was composed of dark gray clayey soil with some limestone and calcite fragments. Particle size analysis showed that the clay content of the slip zone varied from 22% to 39%, and its gravel content was 20% to 35%. It is noteworthy that major part of the slip zone was above the reservoir water level when first impoundment of the reservoir reached the water level of 135 m A.S.L.

The lower section of the slip zone occurred sub-horizontally and slightly inward to the slope. This section of the slip zone was found to be a newly formed shear zone across the bedding plane of mudstone, as a result of landsliding. The slip zone was about 100–120 m long, being much shorter than the upper section, which was 600–650 m long. Materials of the slip zone consisted of dark reddish clayey soils with mudstone fragments. Different from the upper section of the slip zone, this part of the slip zone was fully immerged by the reservoir water when first impoundment of the reservoir reached the water level of 135 m A.S.L.

Additionally, boring revealed that the bedrock immediately under the main slip zone, about 1–2 m thick, was very fractured, while the bedrock deeper was slightly fractured, indicating that the bedrock immediately below the slip zone was much more permeable.

Shear strength of the landslide's main slip zone was examined in laboratory (Table 9.1). Shear strength components of the undisturbed samples from the upper section of the slip zone under their natural and saturated states were determined using the direct shear test, and those of the samples collected from slightly weathered mudstone near the lower section of the slip zone, under their naturally dry and saturated states, were measured using triaxial test.

Table 9.1 Shear strength components of the Qianjiangping landslide's main slip zone

	Saturated		Unsaturated	
Slip zone	Cohesion (kPa)	Internal friction angle (°)	Cohesion (kPa)	Internal friction angle ϕ (°)
Upper section	72.51	13.54	114	16.66
Lower section	112.8	20.8	1500	33.1

Analysis Methods

To compare quantitative effects of the reservoir impoundment and rainfall on the Qianjiangping landslide, a sensitive analysis was performed considering interrelationships between the factor of safety (FS) of the landslide and a series of parameters susceptible to the interactions between the landslide's materials and water from the two sources. The FS of the landslide was computed based on two-dimensional limit equilibrium model (2DLEA) using the Janbu method, one of the most popular methods for the landslides with non-circular slip surfaces. The 2DLEA was implemented using the software SLOPE/W developed by GEO-SLOPE International. The 1-1 cross section through the toe and crown of the landslide was used for computation (Fig. 9.2).

Based on characteristics of the Qianjiangping landslide, the parameters changed due to the reservoir impoundment and rainfall should have include unit weight of landslide materials, cohesion and internal friction angle of the slip zone, pore-water pressure at the slip zone due to rise of groundwater above the slip zone, and uplift pressure of the reservoir water when it saturated the fractured bedrocks underlying the slip zone. As mentioned above, the Qianjiangping landslide main slip zone was made up of two distinct sections: the upper section along a pre-existing shear zone within shale and the lower section across a bedding plane of mudstone. Apparently, the shear strength of the two sections operated during landsliding should be the residual strength of the pre-existing shear zone interbedded by shale, and the peak strength of mudstone, respectively. Accordingly, values of the seven parameters of the landslide were changed following the reservoir impoundment and rainfall.

To evaluate sensitivity of the FS of the landslide to the seven parameters, and the quantitative effects of the reservoir impoundment and rainfall on the Qianjiangping landslide, sensitive index (SI) and effect index (EI) were introduced in this study

$$\mathrm{SI} = (\eta_1/\eta_2) \times 100\% \tag{9.1}$$

where $\eta_1 = |\Delta\mathrm{Fs}| \times 100\%/\mathrm{Fs}_0$, $\eta_2 = |\Delta X_i| \times 100\%(X_{i\,\max} - X_{i\,\min}).\eta_1$, η_2 represent the variation ratio of the FS of a landslide and a parameter, respectively. ΔX_i is variation of the parameter X_i, $X_{i\,\max}$ $X_{i\,\min}$ represent its maximum and minimum values Fs_0 is the initial value of FS of a landslide, $\Delta\mathrm{Fs}$ is the variation of FS resulted from ΔX_i:

$$EI = \Delta Fs_{max,Xi} \times 100\% / \Sigma \Delta Fs_{max,Xi} \quad (9.2)$$

where $\Delta Fs_{max,Xi}$ is the maximum variation of FS when change of parameter X_i reaches its maximum value.

As mentioned before, the landslide took place 43 days after impoundment of the Three Gorges reservoir and a prolonged rainfall during the period between June 21, 2003 and July 11, 2003. This gives three indications: (a) groundwater within the landslide from both the reservoir water and rainfall had fully interacted with the landslide materials before landsliding; (b) influence of the reservoir impoundment on the landslide took place earlier than the rainfall; (c) and the landslide remained stable after the reservoir impoundment and before rainfall. Therefore, the initial state of the landslide for the sensitive analysis in this study was designated to be the moment when the reservoir water level reached 135 m A.S.L., the design water level of the Three Gorges reservoir's impoundment. Accordingly, initial values of the seven parameters aforementioned were as follows: (a) zero for both pore-water pressure at the slip zone above the reservoir water level and uplift pressure of the reservoir water; (b) natural and saturated unit weight of the landslide materials for those above and below the reservoir water level, respectively; (c) the residual shear strength components of the clay seam within the shale at its natural (unsaturated) state for the upper section of the slip zone; and (d) the peak shear strength components of the mudstone at its natural dry state for the lower section of the slip zone.

Assuming rainfall before landsliding fully infiltrated into the landslide and caused the rise of the groundwater table above the slip zone above the reservoir water table, the upper section of the slip zone, primarily, caused an increase in pore-water pressure at the slip zone. Thus, rainfall of 162.7 mm before landsliding caused a maximum rise of groundwater table of 16.3 cm, and as a result, a maximum increase of pore-water pressure. Given that the reservoir water gradually infiltrated into the fractured bedrock immediately below the slip zone following the reservoir impoundment, when the water in Qingganhe River rose from 95 to 135 m A.S.L, the uplift pressure of reservoir water reached its maximum value of 400 kPa. Because pore-water pressure resulted from rainfall infiltration directly corresponding to the rise of groundwater level above the slip zone, this parameter was represented using

Table 9.2 Parameters for the sensitive analysis

Parameters (X_i)	Range
Unit weight of the materials above the reservoir water level (X_1)	17.6–23.6 kN/m^3
Cohesion of the slip zone's upper section (X_2)	114–72.5 kPa
Internal friction angle of slip zone's upper section (X_3)	16.7–13.5°
Groundwater level above the slip zone (X_4)	0–16.3 cm
Cohesion of the slip zone's lower section (X_5)	1500–112 kPa
Internal friction angle of slip zone's lower section (X_6)	33.1–20.8°
Uplift pressure due to reservoir impoundment (X_7)	0–400 kPa

rise of groundwater level in this study. Moreover, shear strength components of most of the upper section and all of the lower section of the landslide's slip zone reached their lowest values when they were saturated by rainfall and the reservoir water, respectively. Ranges of these parameters for the sensitive analysis are given in Table 9.2.

Results and Discussion

Computation yielded an FS of 2.43 when the landslide was at its initial state. When the parameters changed from their initial values following the reservoir impoundment and rainfall, the FS of the landslide linearly decreases (Figs. 9.3–9.7). However, decrease of the FS with change of each parameter varies greatly due to difference in both range of each parameter and effects of the reservoir impoundment and rainfall on the landslide. For the parameters to have the same unit, specifically shear strength components of the upper and lower sections of the slip zone, it seems that the FS is more sensitive to shear strength components of the upper section than those of the lower section in terms of unit variation of these counterpart parameters

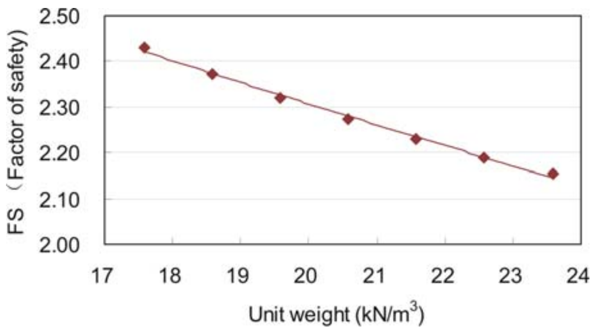

Fig. 9.3 Correlation between FS and unit of weight of the landslide's material

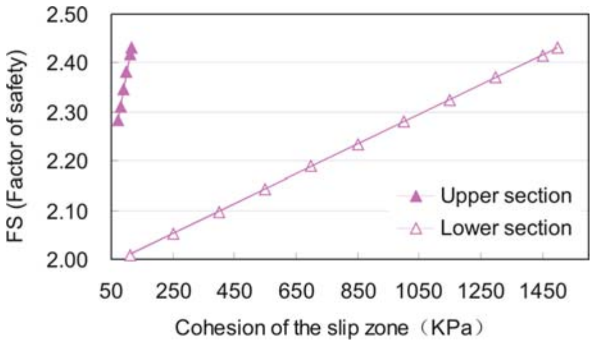

Fig. 9.4 Correlations between the FS and cohesions of the landslide's slip zone

Fig. 9.5 Correlations between FS and internal friction angles of the landslide's slip zone

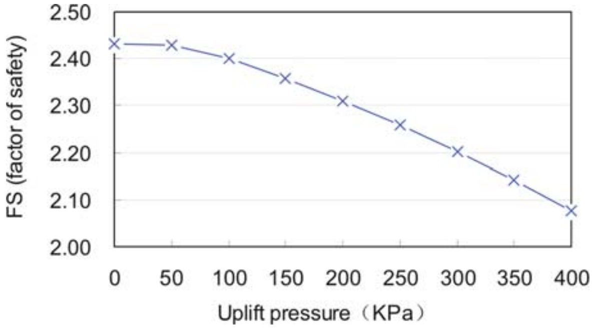

Fig. 9.6 Correlations between FS and groundwater level above the landslide's slip zone

(Figs. 9.3 and 9.4). But, this may not represent the real situation because variation range of each pair of the parameter was very different during development of the landslide. In addition, note that the FS of the landslide showed no change when uplift pressure was less than 50 kPa, corresponding to the reservoir water level below 100 m A.S.L. This is because the toe of the landslide's slip surface was above 100 m A.S.L.

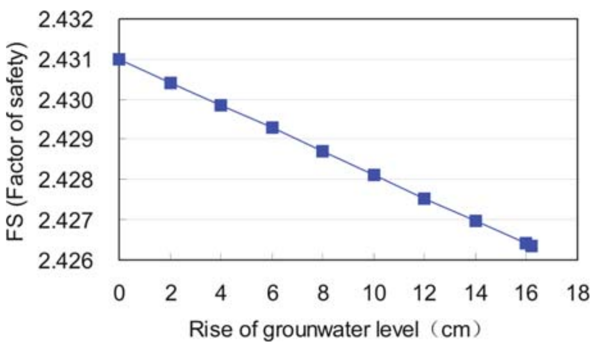

Fig. 9.7 Correlations between FS and uplift pressure of the reservoir water

Sensitivity of the FS to the Parameters Within the Reservoir Impoundment and Rainfall

Figure 9.8 shows the correlations between the variation ratios of FS and those of the seven parameters after the reservoir impoundment and rainfall. Apparently, the slope of each correlation curve represents a sensitive index (EI) of FS to each parameter as defined in this chapter, which considers both each parameter's variation range and its correlation with FS. It is clearly seen that in the range of these parameters, the FS of the landslide was the most sensitive to cohesion of the lower section of the slip zone, followed by uplift pressure, unit weight of the landslide material, internal friction angles of the upper and lower sections of the slip zone, and cohesion of the upper section of the slip zone. The FS of the landslide was the least sensitive to groundwater level above the slip zone. When change of these parameters reached their maximum or minimum values, ratio of maximum decrease of the corresponding FS also demonstrates a similar trend (Fig. 9.9).

Consistent with FS sensitivity to each parameter, effects of these parameters' change on the landslide's stability exhibit a very similar order in terms of effect index (EI) as defined in this chapter (Fig. 9.9): (a) EI of the cohesion of the lower section of the slip zone was the greatest (27.8%) and EI of the groundwater level above the slip zone was the least (0.3%). EI of other five parameters on the landslide were relatively moderate, specifically, 38.1% for shear strength components of the lower section of the slip zone, 23.3% for the uplift pressure, 20.1% for the shear strength components of the upper sections of the slip zone, and 18.3% for

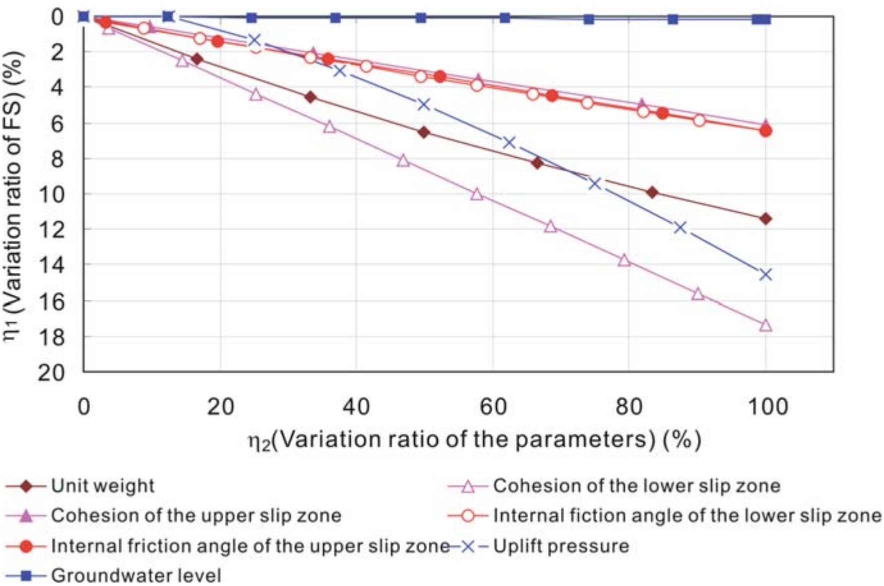

Fig. 9.8 Correlations between ratio of the FS variation and that of the parameters

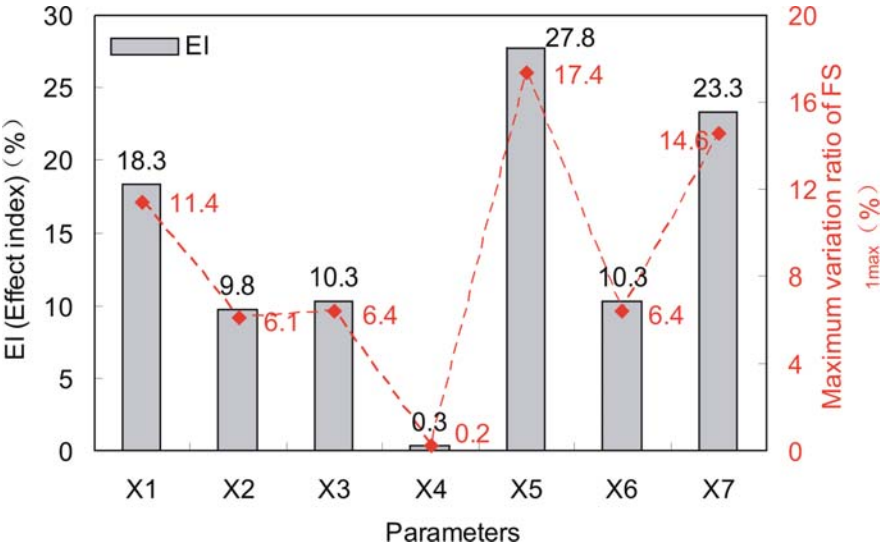

Fig. 9.9 Variation of the maximum ratio of FS and EI of the parameters (denotations of the parameters X_1–X_7 are shown in Table 9.2)

unit weight of the landslide's material. These results suggest that reduction of shear strength of the lower section of the slip zone, particularly reduction of its cohesion component, was the most significant for the landslide occurrence, next were loading of uplift pressure of the reservoir water, reduction of shear strength of the upper section of slip zone, and increase of unit weight of the landslide's materials above the reservoir water level. The rise of groundwater level above the slip zone, i.e., increase of pore-water pressure at the slip zone, seems to be insignificant to occurrence of the landslide. Both reduction of shear strength of the landslide's slip zone and loading of the uplift pressure of the reservoir water resulted in the decrease of shear resistance of the landslide, particularly shear resistance of the lower section of its slip zone, which was the most crucial for the landslide's occurrence. On the other hand, increase of unit weight of the landslide's material led to an increase of driving force of the landslide. As a consequence, a combination of these effects resulted in sudden occurrence of the landslide. Nature of occurrence and the materials of the landslide's slip zone suggest that shear strength reduction of the lower section of the slip zone should be largely the result of water weakening the mudstone by water saturation and hydrolysis during and after the reservoir impoundment, and that shear strength reduction of the upper section of the slip zone was mainly attributed to decrease of soil suction when it was saturated by infiltrated rainfall.

Quantitative Roles of the Reservoir Impoundment and Rainfall in Occurrence of the Landslide

As mentioned before, for the Qianjiangping landslide, the following changes were largely initiated by infiltration of rainfall: increase of unit weight of the landslide's materials, decrease of shear strength of the upper section of the slip zone, and rise of groundwater table above the slip zone, while these changes resulted from the reservoir impoundment: shear strength reduction of the lower section of the slip zone and loading of uplift pressure of the reservoir water. Figures 9.3–9.7 show that the FS of the landslide was still greater than 1, and even greater than 2 if each parameter reached its maximum or minimum values individually, i.e., the worst situation for the landslide's stability. This gives the indication that the landslide was stable. When all the parameters reached their maximum or minimum values simultaneously, the FS of the landslide was reduced to 0.95 from 2.43, suggesting failure of the landslide. The latter situation was actually more close to reality, as it happened on the landslide. Hence, the landslide's occurrence must have been the consequence of the combined effects of both the reservoir impoundment and rainfall. Consequently, for the landslide, effect indices (EI) of the parameters susceptible to the reservoir impoundment and rainfall were 61.3% and 38.7%, respectively, giving a clear indication that the reservoir impoundment played a much more important role in the landslide's occurrence than rainfall. Rainfall may have acted as a triggering factor.

It should be mentioned that the rise of water level of the Three Gorges reservoir to the level of 135 m A.S.L. during its first impoundment must have taken some days, rather finished in a moment. Change of the parameters susceptible to the reservoir impoundment must have taken place before the water level reached 135 m A.S.L. Therefore, the assumption for computation made in this chapter may not fully represent the real situation. Nevertheless, the computation results based on the assumption are of great significance for evaluation of roles of the reservoir impoundment and rainfall, and for understanding their effects on the landslide.

Conclusions

Impoundment of the Three Gorges reservoir and rainfall resulted in changes of a series of parameters for the Qianjiangping landslide susceptible to the interactions between the landslide's materials and water from the two sources. These parameters are as follows: unit weight of the landslide's materials, groundwater level above the slip zone, shear strength components of the slip zone's upper and lower sections, and uplift pressure of reservoir water. Sensitive analysis shows that the FS of the Qianjiangping landslide was the most sensitive to cohesion of the lower section of the landslide's slip zone, followed by uplift pressure, internal friction angles of the upper and lower sections of the slip zone, cohesion of the upper section of the slip zone, and unit weight of the landslide materials. The FS of the landslide was the least for groundwater level above the slip zone. These results suggest that weakening of the slip zone's lower section by the reservoir water contributed the most to the landslide's occurrence. These results further confirmed that the Qianjiangping landslide resulted from combined influences of the reservoir impoundment and rainfall. However, the reservoir impoundment played a more important role than rainfall. The latter may have behaved as a triggering factor.

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References

Dai FC, Deng JH, Tham LG, Law KT, Lee CF (2004) A large landslide in Zigui County, Three Gorges area. Canadian Geotechnical Journal 41(6): 1233–1240

Liu CH, Chen CX, Feng XT (2005) A slope failure due to rise of water level of the Three Gorges reservoir. Rock and Soil Mechanics 26(5): 668–703 (in Chinese)

Wang FW, Zhang YM, Huo ZT, Matsumoto T, Huang BL (2004) The July 14, 2003 Qianjiangping landslide, Three Gorges Reservoir, China. Landslides 1(2): 157–162

Wang FW, Zhang YM, Huo ZY, Peng XM, Wang SM, Yamasaki S (2008) Mechanism for the rapid motion of the Qianjiangping landslide during reactivation by the first impoundment of the Three Gorges Dam reservoir, China. Landslides 5(4): 379–386

Wen BP (2008) Technical report: Characteristics of the slip zones of Qianjiangping landslide and weak zones within the slope adjacent to the landslide (in Chinese)

Xiao SR, Liu DF, Hu ZY (2007) Geo-mechanical model of the Qianjiangping landslide in the Three Gorges area. Rock and Soil Mechanics 28(7): 1459–1464 (in Chinese)

Yang WM, Wu SR, Shi SJ, Pan F (2006) Mechanism of the Qianjiangping landslide in Zigui county, Hubei Province. Coal Mining Engineering 4: 57–59 (in Chinese)

Yin YP, Peng XM (2007) Analysis of mechanism of the Qianjiangping landslide. Hydrogeology and Engineering Geology 3: 51–53 (in Chinese)