Chapter 2
Bank Slope Stability Evaluation for the Purpose of Three Gorges Reservoir Dam Construction*

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Abstract Through working on the classification of the reservoir bank slopes and their deformation mechanism, failure conditions, countermeasure on various types of slope failures, stability analysis and assessment of the bank slopes and large landslides, and monitoring and forecasting, this chapter summarizes the bank slope stability evaluation for the purpose of Three Gorges reservoir dam construction. The exploration and research methods for the evaluation of bank slope stability before the dam construction can be found in this chapter.

Keywords Investigation · Monitoring · Landslide · Rock Fall · Slope stability

Along the two sides of the Three Gorges reservoir on the Yangtze River, there are more than 150 counties and towns. The reservoir is part of the Golden Waterway for outgoing transport from the southwest region of China. Bank slope stability of the reservoir is one of the major geological engineering and environmental geological problems which directly affect the dam construction, the navigation, and the safety of peoples' life and property in the area. The research on bank slope stability in this area has been conducted for more than 30 years since the 1960s. After collaborative research by many departments, many disciplines, with the application of multiple skills, and multiple orders, the problems of the bank slope stability under natural conditions and water storage conditions have been basically clarified and a set of theories and methods for investigation, research, analysis and assessment, monitoring and forecasting have been established.

The research on the bank slope stability of the Three Gorges reservoir includes classification of the reservoir bank slopes and their deformation mechanism, failure conditions, control factors of various types of bank slopes, stability analysis and assessment of the bank slopes and large landslides, risk assessment of the bank slope

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* This paper is translated from the book: Geological Study for the Three Gorges Project, which was published in Chinese in 1997.

F. Wang, T. Li (eds.), *Landslide Disaster Mitigation in Three Gorges Reservoir, China*, Environmental Science and Engineering, DOI 10.1007/978-3-642-00132-1_2,

Investigation and research on stability of reservoir bank slopes	Study on geographical and geological environment of the reservoir bank slopes	Regional geologic features	Geomorphologic type unit
			Strata and distribution
			Geological structure
			Seismic activity
			Climate
			Hydrology
		Geological environment characteristics of the reservoir bank slopes	Basic characteristics of the rock and soil
			Characteristics of geological structure
			Geomorphologic features of river valley
			Characteristics of groundwater
			Dynamic environmental features
	Investigation and research on stability of the reservoir bank slopes	Type of the reservoir bank slopes	Level 1 division–Based on lithology in the reservoir bank slopes
			Level 2 division–Based on the relationship between river valley direction and attitude of strata.
		Research on evolution mechanism of the reservoir bank slopes	The main types and evolution mechanism of the reservoir bank slopes
			Analysis on evolution mechanical process of the reservoir bank slopes
			Present stability of the reservoir bank slopes
		Assessment of stability of the reservoir bank slopes	Stability determination of the different type of reservoir bank slopes
			Probability statistic (quantitative)analysis of the reservoir bank slopes
			Stability quantitative prediction and assessment of stability of the reservoir bank slopes
	Investigation and research on stability of the rock falls, landslides on the reservoir bank slopes	Type and distribution of the bank slope deformation	Landslide features
			Characteristics of rock falls and dangerous rocks
			Size of rock fall and landslide
			Characteristics of geography
			Relations with lithology
			Relationship with geological structure
		Structural Characteristics of rock fall and landslide	Type of rock mass
			Structural characteristics of rock mass
			Hydrogeological characteristics
			Physical and mechanical characteristics of the soil in sliding zone
		Analysis on evolution process of rock fall, landslide	Analysis on forming mechanism
			Special research on typical landslide
			Analysis on active age of landslide
		Analysis on reactivation mechanism of rock fall and landslide	Heavy storm-induced agencies
			River erosion
			Water level fluctuation
			Loading on the back top
			Human engineering activities
		Deformation monitoring of rock fall and landslide	Ground monitoring
			Underground monitoring
		Analysis on stability of rock fall and landslide	General geological analysis
			Stability Calculation and numerical analysis
		Prediction analysis on the risk by the reservoir bank slope failure	Impact on the reservoir storage capacity and lifetime
			Impact on construction and running of the hub buildings
			Impact on navigation
			Impact on resettlement of the towns and immigrants in the reservoir area

Fig. 2.1 Investigation and research approaches for the Three Gorges reservoir bank slope stability analysis

failure, and monitoring technique and forecasting models of bank slope deformation as shown in Fig. 2.1.

Types of Reservoir Bank Slopes and Assessment of the Stability Conditions

Types and Characteristics of the Reservoir Bank Slopes

Up to 5,000 km of bank slope length, including mainstream and tributaries of the Three Gorges reservoir, crossed different geomorphologies and tectonic units. The crystalline rocks, carbonate rocks, scattered rocks, and loose deposits compose the various geological types of the reservoir bank slopes. Deformation and damage to the bank slope are mainly controlled by the rock and soil types and their complexities, the slope form, structural planes and their relationship to the slope surface.

The Three Gorges reservoir bank slopes can be classified into four major types: soil slope, clastic rock slope, carbonate slope, and crystalline rock slope.

Based on the structure of rock and soil and the attitude of the rock and soil beds on the slopes, slopes can be further subdivided into sub-types:

I. Soil slope
   - I_1 Alluvial and pluvial sand and gravel bank slope
   - I_2 Slide and fall accumulations or breccias and fragments bank slope
   - I_3 Thick residual and talus breccia and fragment bank slopes

II. Detritus rock slope and III carbonate slope
   - II_1, III_1 Gentle bed slope (dip angle less than 10°)
   - II_2, III_2 Transverse slope (the angle between rock dip and slope dip greater or equal to 60°)
   - II_3, III_3 Consequent slope (the angle between rock dip and slope dip less or equal to 30°)
   - II_4, III_4 Reverse slope (the angle between rock dip and slope dip greater or equal to 150°)
   - II_5, III_5 Diagonal slope (the angle between rock dip and slope dip between 30° and 60° or between 120° and 150°)
   - II_6, III_6 The rock slope of special structure (referring to the slope with broken rock or the slope with soft base)

IV. Crystalline rock slope
   - IV_1 Magmatic rock slope with massive structure
   - IV_2 Metamorphic rock slope with massive structure.

Among the reservoir bank slopes of the mainstream and major tributaries, the soil slope is 140.5 km long, accounting for 4.69% of the total length; bedded rock slope is 2,368.6 km long, which is 79.06% of the total length; layered carbonate slope is 454.5 km long, which is 15.18% of the total length; crystalline rock slope is 32 km long, which is 1.07% of the total length. It should be noted that the width and the thickness of loose deposits of the soil slope composition are limited; the lower and the upper on the soil slope are still bedrock.

Assessment on Stable Conditions of the Reservoir Bank Slopes

The main types of deformation and damage along the reservoir bank slopes are bank slope rock falls and landslides. Bank slope rock falls mainly occur in the zone of river alluvial deposits, which distributes in small areas of small thicknesses and as long and narrow strips along the Yangtze River. After the reservoir storage, and exposure to long periods of saturation in water and effects of the fluctuation of the water level, the bank slope would experience small-size rock falls. In the trunk stream of the reservoir, there are only 13 sections of possible collapsed bank slopes for the total 12 km long area. The width of the predicted collapse zone is 20–86 m and the total volume of collapse is about 6 million m^3. The erosion of the bank slope surface is manifested as slow and long-term evolutionary processes. The most intuitive signs of the bank slope stable conditions (good or bad) are the developmental characteristics of landslides. When zoning by bank slope stable conditions, some of the main consideration factors are lithology and complex geological structure, types of rock structure, relation between attitude of rock bed and valley direction, deformation and damage degree, number and stability of the existing landslides, and possible changes under the effect of water level fluctuation. Based mainly on geological recognition combined with numerical analysis (mainly for stability of landslides), the stable conditions of the reservoir bank slopes can be divided into four types: good (A), general (B), poor (C), and bad (D) (Table 2.1).

Bank slope in a condition of good stability (A): Lithology and complex slope structure and slope shape are all of benefit to slope stability. Minor in deformation and damage degree, rare in the landslides with a size of more than 1 million m^3; good in the overall stability of existing landslides as well as few in number and small in size of possible newly created landslides during construction and operation of the reservoir. This type of bank slope is 4,271.4 km long, accounting for 85.8% of the total length.

Bank slope in general condition of stability (B): Lithology and complex slope structure and slope shape are all of benefit to slope stability. Medium in deformation and damage degree, rare in the landslides with size of more than 1 million m^3, these mostly belong to stable or generally stable ones. This type of reservoir bank slope is stable, on the whole. During the construction and operation of the reservoir, only a small number of medium- to small-sized landslides would be of poor stability and may fail. There are 76 sections of this type of reservoir bank slopes with the length of 354.5 km, accounting for 7.0% of the total length. These are 89 km long on the mainstream and 265.5 km on the tributaries.

Bank slope of poor stability (C): With soft rock or complex hard and soft rock, slope structure and slope shape have a greater effect on slope stability. This is mostly the case in the number of old landslides, but most of them are no longer active. Poor

Table 2.1 Types of slope stability conditions of the Three Gorges reservoir

Item	Stable condition of the bank slope		Number of sections	Total length	Percentage in the mainstream or the total tributaries in length	Development degree of landslides with a size of more than 1 billion m^3			
	Code	Type				Count	Size	Average line density	Average line Module
Mainstream	D	Bad	6	16.1	1.2	16	24,934.0	0.99	1,548.7
	C	Poor	9	116.0	8.9	52	110,478.9	0.45	952.4
	B	General	5	89.0	6.9	22	131,56.5	0.25	147.8
	A	Good		1,078.9	83.0	46	21,659.6	0.04	20.1
Tributary	D	Bad	31	56.3	1.5	31	34,738.7	0.55	617.0
	C	Poor	93	165.2	4.5	95	57,519.4	0.58	348.2
	B	General	71	265.5	7.2	34	17,044.8	0.13	64.2
	A	Good		3,192.5	86.8	24	11,745.0	0.008	3.7

stability is in a small number of the landslides among the ones with volume of more than 1 million m^3, they may be partially damaged during construction and operation of the reservoir. The bedrock bank slopes may partially collapse. There are 102 sections of this type of reservoir bank slopes with the length of 281.2 km, accounting for 5.6% of the total length. They are 116 km in length on the mainstream and 165.2 km long on the tributaries.

Bank slope in bad condition of stability (D): With soft rock or complex hard above and soft below rocks developing cracks. Slope structure and slope shape are primary conditions for deformation and damage. There is presently a higher degree of deformation and damage or large-size landslides that have reactivated recently (such as Jipazi landslide, Xintan landslide) or deformation is developing (such as Huanglashi landslide, Lanziya dangerous rock mass). In natural circumstances or construction and operation of the reservoir, serious falls and slides or local rock falls and slides may occur. There are 37 sections of this type of reservoir bank slopes with the length of 72.4 km, only accounting for 1.5% of the total length. These are 16.1 km long on the mainstream, accounting for1.2% of the total mainstream bank slope length.

In addition, during the scientific and technological research on "the 5th Five-Year Plan," the "information quantities method," "logic information method," "fuzzy math method," "risk probability analysis," "numerical analysis," "multi-factor comprehensive evaluation," and other methods are applied for assessment and analysis of stability of partial reservoir bank slopes; the results are generally closed to the geological macro-reorganization, as shown in Table 2.2.

Table 2.2 Evaluation results of the bank slope stability on the Three Gorges reservoir

No.	Evaluation method		Evaluation result: Percentage of the bank slope of poor or bad stability	Evaluation result: Percentage of the bank slope of general or good stability
1	The "information quantities method"		7.43	92.57
2	Logic information method		8.69	91.31
3	Fuzzy math method (Zhongxian to Jiangjin tributary)		0	100
4	Multi-factor comprehensive evaluation (reservoir until Fengjie)		12.7	87.3
5	Quantitative assessment for the important sections	Comprehensive assessment System Predicted diagnostic system	Mostly belong to stable type or generally stable type	

Rock Falls, Landslides, and Dangerous Rocks

The bank slope is composed of Quaternary loose accumulation and structural broken rocks and is a minor presence in the Three Gorges reservoir. The flow-related damages such as mud–rock flow and debris flow are not widespread, and it may be of small size or sporadic occurrences. Therefore, the main deformation and damage to the Three Gorges reservoir bank slopes are rock falls, landslides, and a few of dangerous rocks in deformation condition, which are the main subjects that have been researched for stability.

Rock falls can be divided into two forms, rock falls and falls, based on their initiation. Landslides can be divided into two forms, rock landslides and loose deposit landslides, based on their lithology, of which the rock landslides can be further divided into two forms, those of bedding landslide and bed-cutting landslides, based on the relation between sliding surface and bedrock attitudes.

In total, there are 684 rock falls, landslides, and dangerous rocks with a size larger than 100,000 m^3 that are distributed on the 1,300 km long mainstream and the 3,679.5 km long tributary bank slopes of the Three Gorges reservoir. The total volume is 3.04 billion m^3, the average line density 0.14 km^{-1}, and the line module 61×10^7 m^3 km^{-1}. There are 215 landslides with the total size of 1.73 billion m^3, the average line density of 0.17 km^{-1}, and the line module of 133×10^7 m^3 km^{-1} on the mainstream, while there are 469 landslides with the total size of 1.31 billion m^3, the average line density of 0.13 km^{-1}, and the line module of 35.5×10^7 m^3 km^{-1} on the tributaries (Table 2.3).

Individual size of the landslides can be divided into four degrees according to the practices in the Three Gorges reservoir: huge size – size larger than 0.1 billion m^3, large size – size between 10 and 100 million m^3, medium size – size between 1 and 10 million m^3, and small size – size between 0.1 and 1 million m^3.

There are 4 huge landslides with a total size of 0.63 billion m^3 on the mainstream and tributary bank slopes, 53 large ones with a total size of 1.4 billion m^3, 263 medium ones with a total size of 0.88 billion m^3, and 364 small ones with a total size of 0.12 billion m^3. The small landslides take up 54% of the total in number, but only 4% for volume, which indicates that those sizes of more than 1 billion m^3 play a key role in the reservoir bank slope stability.

Counting by types, there are 552 landslides with a total size of 2.78 billion m^3, 126 rock falls with a total size of 0.25 billion m^3, 6 dangerous rocks with a total size of 7.86 million m^3, accounting for 80.7%, 18.4%, 0.9% in total number and 91.6%, 8.2%, 0.2% in total size respectively. Thus, the landslides, mostly bedrock bedding ones, are the main deformation and damage type affecting the reservoir bank slopes which have a total size of 1.89 billion m^3, accounting for 62% of the total size of landslides (Table 2.4).

The distribution of 57 huge and large landslides on the mainstream and tributaries of the Three Gorges reservoir is shown in Fig. 2.2, the size of them in Table 2.5.

Distribution Features of the Landslides

Geographical Distribution

Intensity of the landslides on the reservoir bank slopes is controlled by the conditions of lithology, geological structure stratigraphy, and so on. This is indi-

Table 2.3 Number and size of rock falls, landslides, and dangerous rocks on the bank slope of the Three Gorges reservoir

Ordering in size	Number/size (m^3)					Line density	Line module
	<100 (small)	100–1,000 (medium)	1,000–10,000 (large)	>10,000 (huge)	Total	No. km^{-1}	$10^4 m^3 km^{-1}$
Mainstream	79/2,644.1	105/38,425.9	28/87,449.6	3/44,333.0	215/172,852.6	0.17	133.0
Tributaries	285/9,619.0	158/49,269.7	25/52,758.3	1/19,020	469/13,066.9	0.13	35.5
Total	364/12,263.1	363/87,659.6	53/140,207.9	4/63,353	684/303,519.5	0.14 (average)	61.0 (average)

Table 2.4 Statistic of the rock falls, landslides, and dangerous rocks on the bank slopes of the Three Gorges reservoir

Type		Landslide: Loose deposit landslide	Landslide: Bedrock landslide: Bedding	Landslide: Bedrock landslide: Bed-cutting	Rock fall	Dangerous rock	Total
Mainstream	No.	22	101	40	48	4	215
	Size	11,488.5	133,563.4	14,224.5	13,029.2	547.0	172852.6
Tributaries	No.	203	92	94	78	2	469
	Size	31,494.6	55,512.0	31,626.5	11,792.5	239.3	130,666.9
The whole total	No.	225	193	134	126	6	684
	%	32.9	28.2	19.6	18.4	0.9	100%
	Size	42,983.1	189,075.3	45,851.0	24,821.6	786.5	303,519.5
	%	14.2	62.3	15.1	8.2	0.2	100%

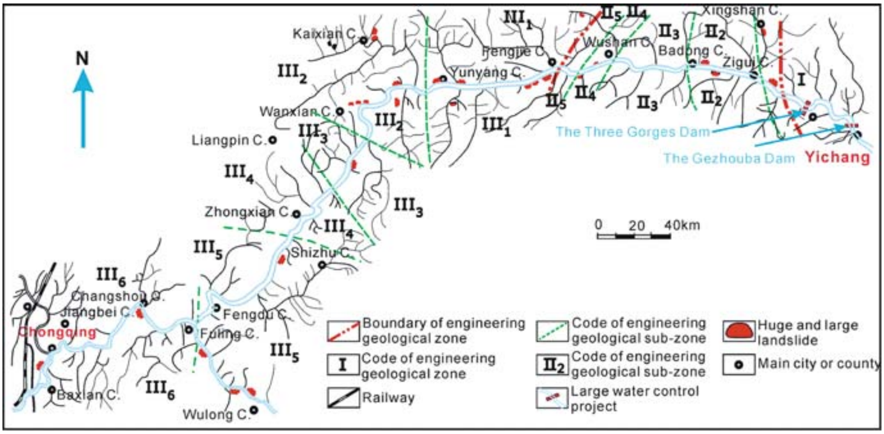

Fig. 2.2 Distribution of huge and large landslides on the Three Gorges reservoir bank slopes

cated by an evident regional deference that the large and medium landslides are concentrated in some areas while rare in other areas. For example, there is only one small rock fall on the approximately 50 km long bank slope from Sandouping to Xintan, a few landslides on the north bank slope from Yaowanxi to Shazhenxi, the Wuxia Gorge and Qutangxia Gorge, the valley from Taoyuan, Fengdu city to Chaotianmen Chongqing city, and no landslides on the 48 km long north bank slope from Sandengzi to Dahegou. The eight portions of the river bank slopes which are Shuping, Zigui county to Huanglashi, Badong county; Laoshucuo to Dawan, Huangguashu to Liujiawuchang, Wushan county; Baiyi’an, Fengjie county to Maohelin, Yunyang county; Baota to Xinlongtan, Yunyang county; Wanxian urban area; Daxikou to Shierchong, Wanxian city; Miaoshang, Zhongxian county to Chengjiadiaoya, Fengdu county, having total length of 151.6 km, make up 11.7%

Table 2.5 Huge and large landslides on the Three Gorges reservoir

		The reservoir bank slopes on the mainstream		
		Landslide No.	Landslide name	Size ($10^4 m^3$)
The mainstream of Yangtze River		2	Xintan	3,000
		8	Shuping	2,360
		14	Fanjiaping	12,500
		16	Huanglashi	1,800
			Huangtupo	4,080
		22	Zuojituo Rock fall	1,353
		27	Xiangjiawan	2,000
		31	Caojiawan rock fall	2,300
		43	Shuizhuyuan	1,700
		49	Liujiawuchang	1,791
		52	Baiyi'an	4,434
		53	Qiancaotuo	3,360
		57	Baihuanping	12,933
		59	Xinpu	6,000
		60	Outang	2,000
		66	Gulingzhen	18,900
		68	Baota	8,500
		69	Jipazi	1,500
		72	Yunyangxicheng	2,500
		76	Jiuxianping	5,220
		87	Yuhuangguan	4,887
		89	Caojiezi	2,283
		90	Anlesi	6,426
		91	Taibaiya	6,220
		92	Diaoyanping Rock fall	1,747
		99	Houcao	3,516
		119	Maoxuzi	3,368
		122	Longwangmiao	1,173
		126	Chengjia Diaoya	1,231
		135	Caofang	1,000
		139	Zhonggangjiaolu	1,420
Tributaries				
	Xiangxi R.	16–32	Shifuosi	1,030
	Guizhou R.	19–1	Kaziwan	3,360
		19–3	Wujiadaling	1,432
		19–7	Hujiawuchangwu	4,308
	Daning R.	48–6	Zaibaozi	1,015.5
		48–18	Lianyuchi	1,020
	Cuokaixia R.	69–3	Dawuchang	1,204
	Daxi R.	75–4	Hualianshu	2,604
		75–10	Xiangshuitan	2,394
		75–11	Yinwozi	1,164
		75–14	Shijiawan	1,292
	Meixi R.	78–15	Baiwafang	2,880
		78–16	Zhichangwan	1,612
		78–17	Longpo	19,020
	Modao R.	105–3	Dashiban	1,075

Table 2.5 (continued)

	The reservoir bank slopes on the mainstream		
	Landslide No.	Landslide name	Size ($10^4 m^3$)
Xiaojiang R.	120–11	Wangjiayuanzi*	2,036
	120–12	Duoxiaoping	4,944
	120–14	Zhoujiayuanzi*	1,492
	120–15	Panjiayuanzi*	2,730
Xongjiagou R.	124–1	Wutongping	1,869.6
Bayangxi R.	125–2	Oujiaping	1,612.5
Huilongxi R.	132–1	Pijiayuanzihuapo	1,795
Wujiang R.	164–9	Wanbeituo	2,863.2
	164–21	Yangjiaotan	1,006
	164–23	Yangjiaozhen Rock fall	4,071
	164–28	Tukan Rock fall	2,128.2

*The reservoir will not affect.

of the whole mainstream, but the landslides on these bank slopes take up 48% in number and 84.4% in size of those on the whole mainstream.

Landslides on the tributary bank slopes mainly occur in the Xiangxi River, Guizhou River, Qingganhe River, Caotang River, Meixi River, and Wujiang River, which take up 44.3% in number and 63.4% in size, of those on the total number of tributaries.

Elevation of the Landslides Distribution

Most landslides occur close to the base of the Yangtze River. For over 97% medium or larger ones on the mainstream, their toes are near the dry water level of the Yangtze River; meanwhile for the 85% of those on the tributaries, their toes are near the river bed. The sliding surface of the Wanxian landslide group occurring in nearly horizontal rock beds has three elevation levels, 190–200 m, 214–224 m, and 240–250 m, corresponding to II – III terraces (Fig. 2.3).

Relationship with the Lithology and Stratigraphy

Rock masses are the material basis of rock falls and landslide formation. Different rock types differ in the intensity of rock fall and landslides. There are no large landslides in magmatic and metamorphic rock bank slopes. Deformation and damage on carbonate bank slopes are relatively weak, and the main damage form is rock falls. In the over 600 km long carbonate bank slope, the landslides account for only 8.2% in number and 5.6% in size of the total. In the 422 km long bank slopes with soft and hard inter-bedded clastic rocks and part carbonate rock having a weak base, the landslides are relatively extensive; their failure form is mainly large and medium,

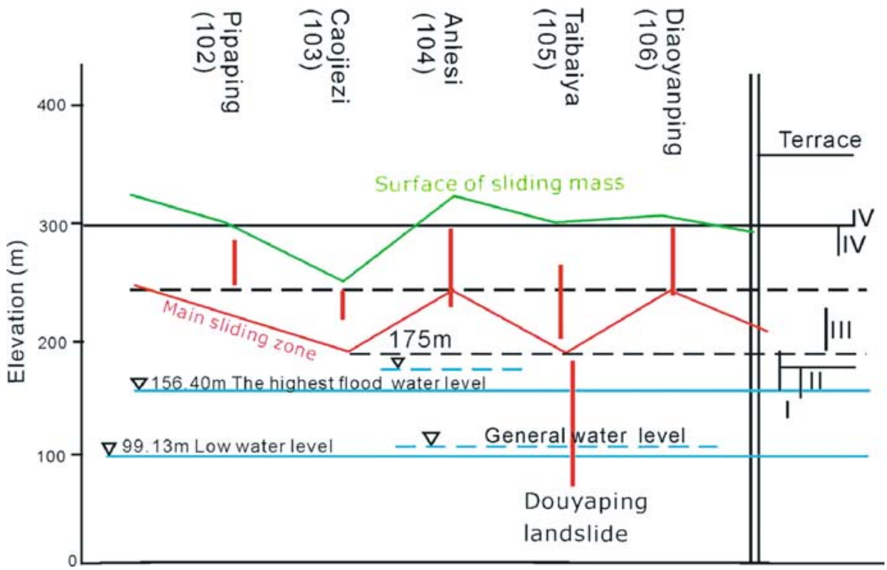

Fig. 2.3 Profile of sliding surface elevation of the old landslides in Wanxian city

which accounts for 87.3% in number and 91.1% in size of those on the total area of the bank slopes. Therefore, as to the distribution area, development extent, and possible damage of the landslides, the bank slopes with bedded clastic rocks rank a main status, and it is the most important area to study for reservoir bank slope stability.

Relationship with Geological Structure

The effect of deformation and damage of the reservoir bank slopes based on geological structure depends mainly on the relative relation between the direction of river flow and the attitude of geological structures. As river flow is consistent with a fold axis, it can form along a strike valley and continue mainly along bedding landslides which concentrate on the bedding dip slope of a syncline wing or a tilted end, such as Fengjie-Guling town and Baota-Xinglongtan bank slopes within the Guling syncline (Fig. 2.4). Meixihe bank slope within the Qumahe syncline and Jinzhuyuan-Tangjiawan within the Fengdu-Zhongxian syncline are all parts of synclines that converge to tilt up toward the east and close increasingly, where they form an "arm-chair" slope structure generally causing large-scale bedding landslides. Daxihe within the Wushan syncline, Taping-Liujiawuchang on the mainstream, Xiangxihe on the margin of the Zigui syncline, Shuping-Fanjiapingduan on the mainstream, and Qingganhe in the Caidianzi syncline are also the regions where landslides are concentrated.

In the river valleys which are cut along the vicinity of an anticline axis, not only landslides and rock falls have developed in the dip sides but a relatively large size

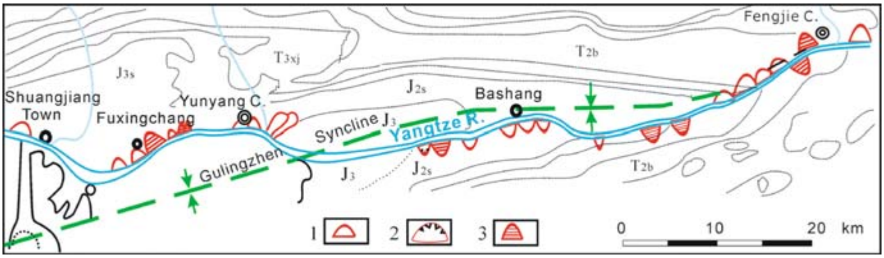

Fig. 2.4 Cases along bedding slope – those landslides developing in the wing or tilted end of syncline. 1 – The landslide with a size of less than 1 million m^3; 2 – the rock fall with a size of less than 10 million m^3; 3 – the landslide with a size of more than 10 million m^3

of landslide could occur in the other reverse dip sides as the cracks paralleling the river bank slope occur and converge with the cracks in other directions as well, based on certain lithologic conditions (e.g., Badong formation). Examples include the Shuping landslide in Zigui county, the Huanglashi landslide in Badong county, etc.

Another important reason for large landslides easily occurring in the core of the anticline in the Three Gorges area is that the anticlines often outcrop with weak shale and coal formation (Silurian, Ma'an Group in Permian) which forms a geological structure of a hard bed lying on a soft base which causes large dangerous rock masses (such as Lianziya dangerous rock mass) and cumulative blocks of rock falls as well as the triggering of large landslides, such as the Xintan landslide and the Xiangjiawan landslide.

In the canyons cutting across anticlines, as the attitude of rock beds drastically changed and small faults densely developed, the area is prone to rock falls and sliding deformation of the rock fall deposits, such as the landslides occurring at Zuojituo, Xiangjiawan, Baiheping, Yaqianwan, which are located in the axis of the Nanmuyuan and the Hengshixi anticlines (Fig. 2.5).

Relationship with the Structure of the River Bank Slope

The structure of the bank slope is a synthetic performance of stratigraphic lithology, geological structure, and valley geomorphology, which directly controls the distribution and development of landslides. The order of the landslide intensity ranging from strong to weak is as follows: dip-slope bedded bank slope, gentle dip and soft base bedded bank slope, reverse slope dip bedded bank slope, and other types. The damage is dominated by landslides that occur on slope dip bedded bank slope and by relative equivalent landslides, for other types of bank slopes. It can be concluded that landslides are evidently defined by the structure of the clastic bank slope, especially the slope dip bedded bank slope is a primary slope type for large landslides; the bank slope containing a soft base in a carbonate area is the zone with densest development of landslides and rock falls.

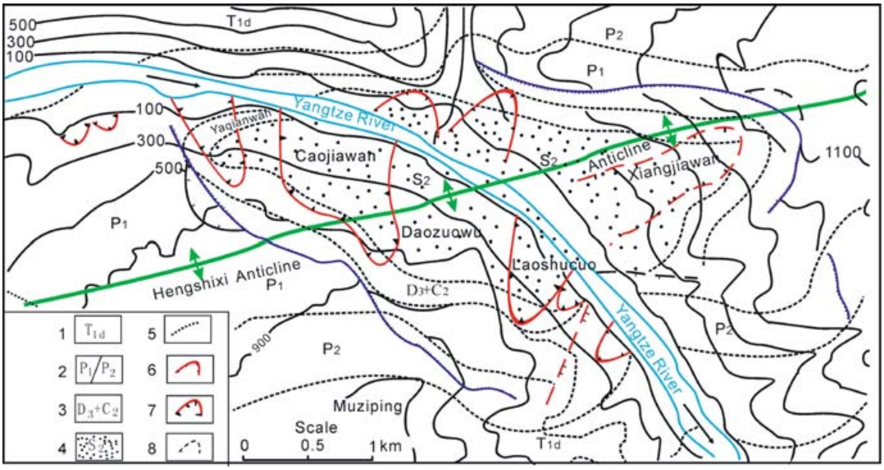

Fig. 2.5 Cases of rock falls concentrated in the anticline cores in the Gorges areas. 1 – Daye limestone in lower Triassic; 2 – limestone in Permian; 3 – sandstone in Devonian and limestone in Carboniferous; 4 – shale in Silurian; 5 – stratigraphic division line; 6 – landslide; 7 – rock fall; 8 – dangerous rock

Structural Characteristics of the Landslides

The greatest number of landslides occurred in loosely structured rock blocks with soil fill. The rock blocks vary in sizes mostly of 0.1–1.0 m in diameter, and larger than 10 m for the large ones. Because of ground water and surface water leaching, the clay content in the lower portion is increasing. As gravity grading and post-filling in the long-term accumulation of the rock falls, the majority may appear faintly discernible beddings.

The soil components of the landslide are controlled by the factors of stratigraphy, lithology, activation times, sliding velocity and run-out distance, variability in material composition, and braking intensity and can generally be divided into six types according to landslide structures (Table 2.6). Broadly speaking, from type 1 to type 5, it generally shows increase in activation times, sliding velocity and run-out distance and decrease in the entirety. For a single case, generally the extent of disintegration in the front and in the surface of the sliding mass is more serious than in the deep position.

Physical and Mechanical Properties of the Sliding Zone

Reactivation of landslides mostly occurs along the original sliding surface (zone), so it is of great significance to research the sliding zone.

Material Composition of the Sliding Zone

Table 2.6 Structural types and characters of the sliding mass

No.	Structural types	Structural characters	Landslide types	Cases
1.	Massive structure	Sliding mass has a good entity of mainly the rock with massive structure, only the depression zone or the front has the rocks with scattered-broken structure.	Rock has beddings of near horizontal or gentle dip, along with bedding landslide.	Landslide of Jiuxianping and landslide group of Wanxian.
2.	Cataclastic-massive structure	There is 70% of sliding mass composition with massive cracked rock, only local part in the front is cataclastic-scattered structure. Colluvium and deluvium can be seen mainly in the rear.	Rock has beddings dipping to slope, with bedding sliding landslide.	Landslides of Baihuanping, Guling, Outang Houcao, etc.
3.	Scattered-cataclastic-massive structure	Rocks with massive-cracked structure are not up to 40%; scattered structure can be seen mainly on surface, in the front and rear or depression zone, with massive-cracked structure mostly located at the base.	With dip structure landslide and cut bedding rock landslide	Landslides of Fanjiaping, Liujiawuchang, Baota, and Cicaotuo.
4.	Cataclastic-scattered structure	Rocks with cataclastic structure and those with scattered structure contaminate each other, in proportion of 2:3, but scattered rocks are located mainly on the surface and in the front and rear.	Rock landslide or its reactivation part.	Landslides of Liulaiguan, Dawan, Jipazi, Xichen, and Taoyuan.
5.	Scattered with cataclastic structure	Rocks with scattered structure have more than 70% occurrence. Scattered rocks distribute mainly in the base or the rear of the sliding mass.	The old landslide reactivating for times. The sliding mass is composed of colluvium, deluvium, and underlying bedrock together reactivating times.	Landslides of Sandengzi, Huangshi, Daping, Anlesi, and Zhonggang.
6.	Scattered structure	Sliding mass is composed of the rock with scattered structure, basically.	The old landslide reacting for times or the deposits of landslides transformed to slides.	Landslides of Xintan, Liyutuo, Diaoya Ping

Mineral Composition

Mineral composition of sliding zones depends on the mother rocks, whose clay minerals and contents are the same as those in the mother rocks. By polarizing identification and differential thermal analysis, the soil in the sliding zone is mainly composed of clay minerals of an average content of 65% and the average content of detrital minerals is 35%. Clay minerals are mainly illite which occurs in an average of 45%, then crypto crystal clay, an average of 20% (Fig. 2.6). Micro-calcite, kaolinite, montmorillonite, and organic matter occur in small amounts. Detrital minerals are mainly quartz, mudstone, siltstone, and sandstone debris and are the second ones.

In addition, the clay mineral in the soil of the sliding zone depends upon the weathering intensity. In weathering crust, the shallower the buried depth, the longer is its history; the looser its structure, the higher is its clay content. Furthermore, the clay mineral content of the sliding zone is also related to the geomorphology and to the buried depth from where the sliding zone occurs.

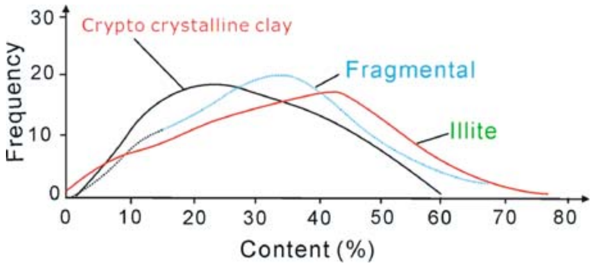

Fig. 2.6 Mineral content in the sliding zones of the landslides on the mainstream of the Three Gorges reservoir

Grain Composition

Engineering geological properties of the sliding zone vary with its grain composition. The granular metric analysis for more than 100 specimens from the sliding zones of the landslides in the Three Gorges reservoir (Fig. 2.7) suggests that gravels and sand content show lognormal distribution with a relative concentrated distribution and little divergence, with the average content of 20%; silts and clays show normal distribution, but the former is high in divergence with the average content of only 25% and the latter is low with the average content of 35%. On the whole, fine grains in the sliding zone of the large landslides in the Three Gorges reservoir are rich; the main grain compositions are clays, and the soil is typically clayey.

Physical and Mechanical Properties

Physical Properties

The soil in the sliding zone is clay whose consistency can change into solid, plastic, and liquid states depending on its moisture content variation.

According to the statistical analysis of the test results for the soil in the sliding zone (Fig. 2.8), both plastic limit and liquid limit show lognormal distribution, with

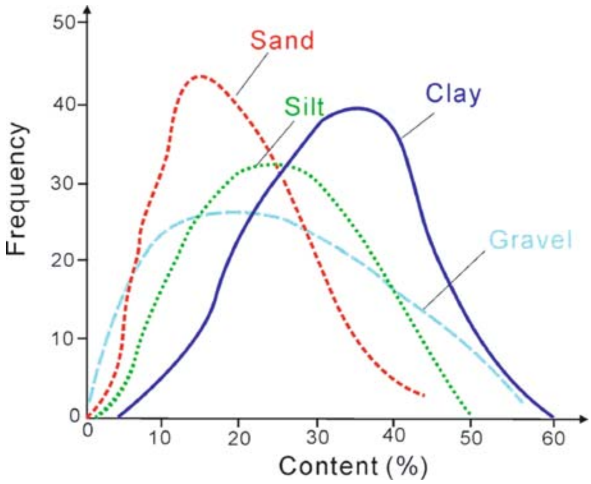

Fig. 2.7 Content of various particles in the sliding zone of the landslides in the mainstream of the Three Gorges reservoir

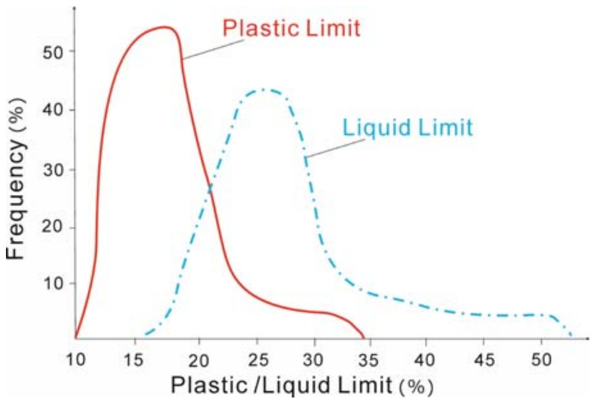

Fig. 2.8 Distribution of plastic limit and liquid limit of the soil in the sliding zone

low divergence and the average value of 27.5% and 17.5%, respectively, the corresponding average plasticity index of 10%, the soil belongs to the clayey category.

Mechanical Properties

Mechanical properties of sliding soil include strength indexes and deformation indexes; the former are the essential parameters for calculating the landslide stability.

The statistical results of the shear strength are presented in Fig. 2.9; it indicates that peak strength shows normal distribution while residual strength shows lognormal distribution with low divergence for both. The average peak value of cohesion (c) is 12.22 kPa and that of friction angle (φ) is 16.78°, while the average residual value of cohesion (c) is 7.96 kPa and that of friction angle (φ) is 13.84°. The general regularity is that the shearing strength of the sliding zone decreases in the order of the sliding zones of the landslides and rock falls with hard rock

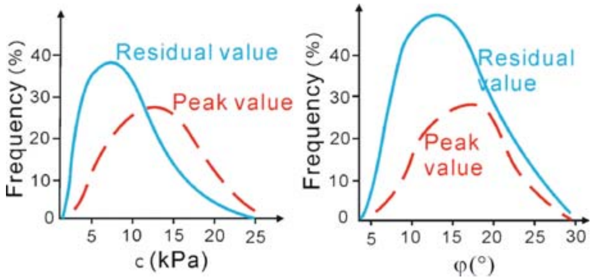

Fig. 2.9 Distribution of c and φ of the soil in the sliding zone

sliding bed (such as landslides of Zuojituo, Yaqianwan), those of the cut beddings landslides (such as landslides of Huanglashi, Shuping), those of rock falls with a shale rock base (such as rock falls of Baiheping, Xiangjiawan), those along bedding, and landslides controlled by coal seams (such as landslide of Fanjiaping), those of accumulative deposit landslides with shale base (such as landslide of Xintan), and along bedding landslide controlled by mudstone bed (such as landslides of Jipazi, Taibaiya, and Zhonggangjiaolu).

The main factors that affect the strength of sliding zones are granular composition, mineral composition, and water content. The effect on the friction angle is shown in Table 2.7 and Fig. 2.10.

To consider the comprehensive effect of various factors on residual strength, a couple model and a regression analysis are also carried out. The results present that

Table 2.7 Factors affecting the shearing strength of sliding zone

Affecting factors		Affecting results
Clay content		The residual friction angle of sliding zones shows prominent negative correlation with clay content; it indicates that the higher the clay content, the stronger the water colloid cohesion, and lower the residual strength.
Mineral composition	Illite	Its content has nonlinear negative correlation with residual friction angle. Content of illite with 38% is the sensitive point (curve inflection point). As less than the point, the residual friction angle is sensitive to illite, while greater than the point, the sensitivity deceases.
	Cryptocrystalline soil	As the context is more than 40%, the effect to residual friction angle is apparent.
	Detrital minerals	Its content has linear negative correlation with residual friction angle.
Water content		Water content has clear nonlinear negative correlation with residual friction angle. There is a sensitive point near liquid limit (24%). Structure of the soil in the sliding occurs mutation when higher than this point.
Structure of the soil and roughness of the particle surface		The soil in the sliding zone with scales texture has low residual friction angle.

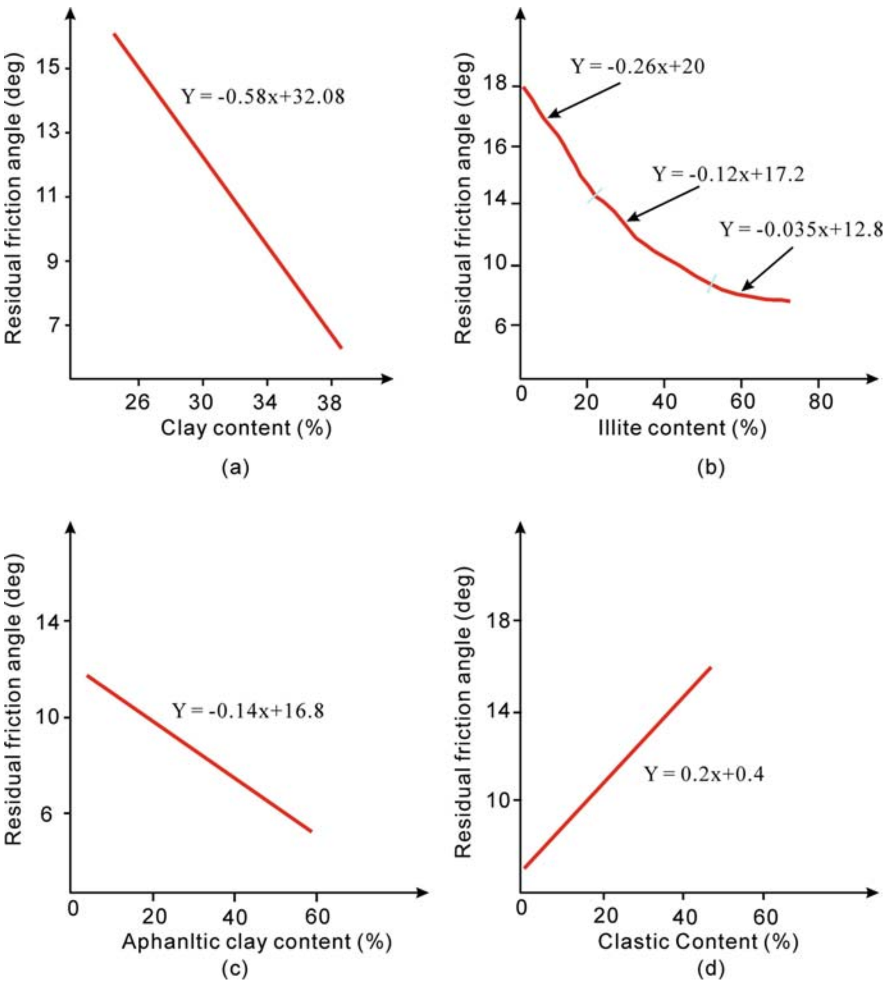

Fig. 2.10 Relations between residual friction angle and the content of clay, cryptocrystalline clay, and detrital mineral

as natural water content of the soil in sliding zone in couple model is near liquid limit, the estimated residual internal friction angle is similar to the one obtained by the consolidation undrained shearing test. The results of the couple model are satisfactory. By the regression model, we can see that the residual strength has linear negative correlation with the logarithm of clay content and of water content respectively, has linear positive correlation with plastic limit. Water content is the most sensitive factor affecting the residual strength of the soil in the sliding zone.

Microstructure Feathers of the Sliding Zone

According to the identification results by polarizing microscopy, microstructure characteristics of the soil in the sliding zone of the landslides in the region can be summarized as the structures of microscopic scale-like, crypto-crystal and micro-crystal. Microscopic scale-like structure is the main type of soil in the sliding zone, in which the clay minerals are mostly scale-like illite, with a directional array, and the array direction has a small angle of intersection with the sliding surface. Contact among the soil particles is mainly face to face, and the attractiveness of the contact is weak and not firm. However, its water tight characteristic can result in water saturation of the sliding zone to cause the advantageous distribution of the weak microstructure planes. For crypto-crystal and microcrystal structures, the former is mainly dispersed crypto-crystal clays, with a few scale-like illites, and a trace of kaolinites, while the latter is mainly microcrystalline calcite, mostly in aggregates or dispersed, secondly it is crypto-clays and micro-scale-like illites.

Hydro-geological Characteristics of the Landslides

Landslides in the Three Gorges reservoir often contain ground water, where water-bearing capability, permeability, recharge and discharge conditions, and water level variation are the important factors affecting the present deformation and stability.

Landslides are mainly loose deposits, in which the ground water occurs mainly as pore water with the buried condition of phreatic aquifer. Also, there is fissure water in the rock with a massive structure. The conditions of the ground water movement and discharge are not only controlled by rock properties and structures but also affected by terrain, river water level, and hydrogeological characteristics of the underlying bedrocks.

Water-Bearing Capacity and Permeability of the Landslides

Water bearing capacity and permeability of the landslides are confined by material composition and structure type of the sliding mass and have a relatively high anisotropy.

Rock Fall Deposits

Rock fall deposits mainly distributed on the sides of deep and steep Gorges are generally composed of stiff and thick rock blocks, contain relatively less fill mud, mostly without water, and are of high permeability. According to borehole results, the rock fall deposits such as Qianya, Xiangjiawan, and Baiheping, contain water locally or in the front, with small water storage capacity and seasonal variation.

Landslide Deposits

Landslide deposits are an open hydrogeological structure on a slope, in which the ground water condition occurs as the relation between the slope runoff surface and the slope sliding surface, that is, while the slope sliding surface is less than the slope runoff surface, the sliding mass contains water; on the contrary, it contains no water or partially contains water. According to exploration data, ground water gradients in typical and large landslides are generally 0.15–0.27.

Statistical results suggest that the aquifer in the landslide generally has four types:

(1) Ground water bearing. The landslide deposits are saturated annually, but the ground water depth varies in a large range with the type and the size of the sliding mass, the shape of the sliding bed, and the geomorphic position of the landslide. The dips of land surface and the sliding surface for this type of landslide are mostly less than 15°.
(2) Ground water bearing basically. Most of the landslide deposits are saturated annually, but a small part is saturated seasonally. The dips of land surface and sliding surface for this type of landslide are mostly less than 15°.
(3) Partially bearing ground water. A part of the landslide deposit is saturated annually; the other part is saturated seasonally. The land surface for this type of landslide is steep generally, with average dip angle more than 15° in most cases. Sliding surface is greater than 15° overall, mostly more than 20°.
(4) No ground water basically or ground water bearing in the front, seasonally. Most of the sliding mass has no water annually, and is only temporarily saturated during the rainy season. Both land surface and sliding surface for this type of landslide are steep, with dip angles larger than 20°. Most of the sliding mass locates above the flood level of the Yangtze River; in addition, the underlying bedrock has high permeability.

Permeability of landslide deposit obviously differs because of their structural variation. The stiff rocks with cataclastic structure (limestone, sandstone) present serious leakage in the drilling process and show relatively high permeability. The rock with scattered and cataclastic structure in general has low permeability, and the coefficient of permeability obtained by pumping test is 0.01–0.05 m/d.

Recharge and Discharge Conditions of Ground Water in the Landslides

Water sources of ground water recharge in rock fall and landslide deposits include rainfall, surface water (rivers, barrier lakes, paddy fields, etc.) and ground water from the vicinity, of which rainfalls and rivers are the main sources. As permeability of the landslide surface is low, water penetration is relatively homogenous and stable. As it is high and ground fissures exist, the conditions for ground water supply are preferable, and concentrated water supply in space and time may occur, which makes the ground water level rise suddenly, seriously affecting the stability of the landslide, often leading to landslide failure (such as Jipazi landslide).

Discharge conditions of ground water in rock fall and landslide deposits are related to their water convergent conditions, length, thickness, slope angle, cut of gullies, permeability, and spatial attitude. There are about three cases of water drainage:

(1) *Poor drainage condition*: It is large in water convergent basins, not developed in gullies, or developed in gullies, and more in paddy fields and barrier lakes. Permeability of the rock fall and landslide deposits is low.
(2) *General drainage condition*: It is medium in water convergent basin, but developed in gullies; or small in water convergent basins, not developed in gullies. Permeability of the rock fall and landslide deposits is medium.
(3) *Good drainage condition*: It is small in water convergent basin, developed in gullies, or not developed in gullies but there are water-tight covers. Permeability of the rock fall and landslide deposits is good.

Ground Water Fluctuation and Its Affecting Factors

Ground water level in the rock fall and landslide deposits has seasonal fluctuations which are affected by the rainfall, and by both the rainfall and the river, in the front. Ground water fluctuations can be divided into sensitive and non-sensitive types.

(1) *Sensitive type*: It can be further divided into rainfall sensitive type and river sensitive type by the affected agent. For example, the Dabashi slide block of the Huanglashi landslide has the perched water table with a buried depth of 3–17 m and a water saturated thickness of 3.3–20 m. The range of ground water level change is 3–16.4 m, and the peak of spring water runoff has a 2-day delay of the peak of rainfall. The ground water level change in the front of Jipazi landslide is closely related to changes of the river water level, and its range is 20–44 m. See Figs. 2.11 and 2.12.

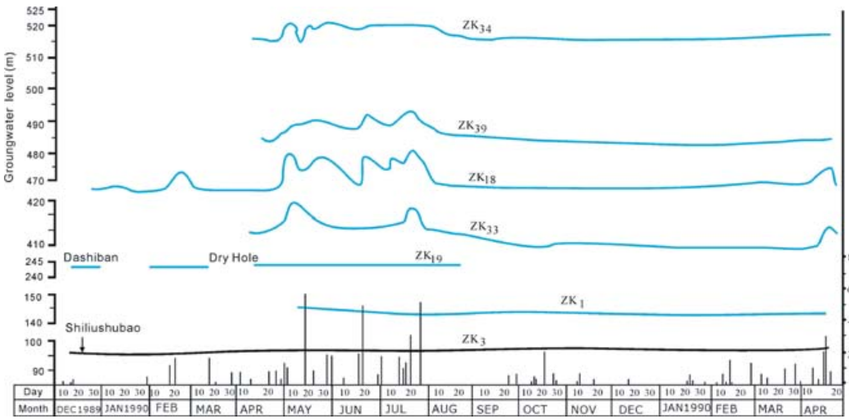

Fig. 2.11 Relationship between ground water level changes in the Huanglashi landslide and the precipitation

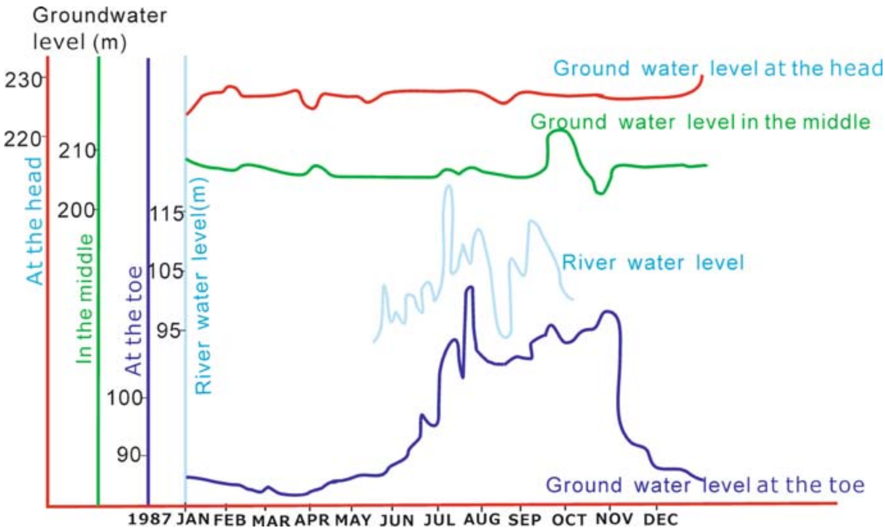

Fig. 2.12 Relationship between ground water level changes in the Jipazi landslide and the river level in 1987

(2) *Non-sensitive type*: Such as the landslides of Chengjiadiaoya and Maoxuzi, the range of ground water level change is 0.4–4.4 m. In addition, some landslides being good in water convergent condition, but poor in land surface permeability, belong to the non-sensitive type.

Looking at the long-term monitoring data, ground water level fluctuation in the typical and large landslide deposits has the following regularities:

(1) The landslide deposits with scattered and cataclastic structures are smaller in annual fluctuation of ground water level while those with massive structures are large.
(2) Those without the river affecting them are smaller in annual fluctuation of ground water level, on the contrary, are larger. According to monitoring information, annual water level fluctuation in boreholes is 1–3 m for the landslide deposits with scattered and cataclastic structures – up to 7–20 m for those affected by river water. It is 4–10 m for those with massive structures, up to 40 m for those affected by river water.

Formation Age of the Landslides

Besides exploring and researching the basic characteristics of the large landslides in the reservoirs, meanwhile, their formation time was also researched. The applied methods are as follows.

Determination of the Absolute Age for the Soil in the Sliding Zone

The age determination results of the soil formed in the sliding zone and the ruptures for the 10 landslides including Huanglashi are shown in Table 2.8. From the results, it can be seen that the ages for different landslides are quite different, but the following preliminary situations can be concluded:

(1) All that have their age determined are older than 8,000 years. Most of the sliding masses in the Three Gorges area are located along both sides of the mainstream and tributaries. Almost no large landslide occurring recently is noted, as the recently failed Jibazi and Xintan landslides are both reactivation of old ones. It seems that deformation and failure on the bank slopes of the Three Gorges reservoir have come to a quite period, after the end of activation.
(2) The absolute age of the soil in the sliding zones is determined mainly by ranges between 27 and 120 thousand years, and it is in accordance with the geological history of the Late Pleistocene (Q_3), the time when the landslides formed.
(3) Comparing the dated ages with the paleoclimate periods, most correspond to warm-humid periods, which show that the landslide formation has a close relationship to the warm-humid time of the paleoclimate.

Table 2.8 The age determination results of some landslides

Geological times	Age ($\times 10^4$a)	The sites for sampling specimens ($\times 10^4$a)
Holocene (Q_4)	Present–1.1	Zhaojiatuo (0.95), Huanglashi (0.8–1.2), Zhongang (1.2)
Late Pleistocene (Q_3)	1.1–13.0	The west of Yunyang county (2.7), Qingyanzi (1.4), Xintan, Jiuxianping, Huanglashi (3.7–6.4), Guling and Quchipan (7.5–13.0), Huanglashi (8.70 rupture)
Middle Pleistocene (Q_2)	13.0–73.0	Qiancaotuo, Daping (19.0), Baihuanping (29.0±), Wanxian landslide group (15.0–30.0)

Referring to the Terraces of Yangtze River Valley

From statistical analysis, the front of the sliding masses in the Three Gorges reservoir rests mostly between the first terrace and the low water level of the Yangtze River. The first terrace sediments and the erosion platform are commonly seen in the front of the sliding mass. Elevations of the main sliding zones and their fronts, for seven old landslides in Wanxian city, correspond to that of the first terrace, and those of land surfaces to the fourth to fifth terraces. From the facts, we may conclude that the sliding mass along the Yangtze River bank slopes was mainly formed in the middle or late Pleistocene, which basically coincides with the determined absolute age above.

Stability Assessment of the Sliding Masses

The main methods to evaluate the sliding mass stability include macro-geologic judgment, stability calculation, failure probability analysis, sensitivity analysis, and fuzzy synthetic evaluation. Whether the results achieved from those methods are correct or not depends on the objectivity and reality for recognizing the factors affecting the stability of the sliding masses, especially in stability calculation, whether the boundary conditions of the slide masses are clear or the selected parameters for computing correctly, directly affects correction of the results. As it is difficult to ascertain landslide boundaries thoroughly and to obtain accurate parameters in practical work, multi-methods are applied for comprehensive assessment to obtain a relatively practical result.

Micro-geologic Judgment

By comparing many cases of landslide failure, it is realized that micro-geologic judgment of sliding mass stability should emphatically take into consideration the following main factors:

(1) With or without apparent deformation and reactivation symptom at present;
(2) Intensity of recent activation and status of post activation;
(3) Shape of the run-out surface and structures of the slope;
(4) Structure of the sliding mass and shape of the sliding surface;
(5) Material sources and the sizes contributing to the landslide material, from the head;
(6) Surface water infiltration and drainage conditions;
(7) Seismic effect and human activity intensity.

Of the factors mentioned above, traces of deformation are the primary mark for stability judgment. The geomorphic characteristics of the sliding mass, such as on-surface inclination, front-surface freedom, gully cuttings, and closed depressions, provide external marks for stability judgment. Dip direction, dip angle and shape of the sliding surface, and ratio of the resistant segment to the total length of the sliding surface are significant indicators for the sliding mass stability judgment, which needs in-site exploration to determine. The investigation of case histories suggested that the landslides with steep plane sliding surface have low stability; those with circular arcs are wave-like; broken line sliding surfaces have medium stability; and those with gentle, long horizontal segment sliding surfaces or with a reverse slope in the front thrust portion usually have good stability. Storm intensity, stream action, human activity, earthquake, and other dynamic environmental processes are the important triggering agents affecting the sliding mass stability.

Calculation by Limit Equilibrium Methods

In the limit equilibrium method calculating landslide stability, the method of inter-force transfer is the principle method used in China. The method considers not only the gravity of the sliding mass but also the hydrodynamic pressure and buoyant force or uplift force of the ground water. The five important landslides including Xintan are also checked with consideration of the potential seismic intensity as seven degrees.

The effects of rainfall and the river water level fluctuation on calculations are considered as following schemes:

(1) In dry seasons, there is no or less rainfall in the area, and the calculation is carried out in natural state;
(2) In rainy seasons, there is continuous rainfall or rainstorm in the area, and the calculation is carried out using a saturated state;
(3) The water level of the reservoir is considered according to the dry water level, 1% frequency of flood level before storage, limit level for flood control and the normal water level after storage, and other kinds of conditions, in the calculation. Also, there is the special circumstance where the water level drawdown from the normal water level decreases the level for purposes of flood control is also considered.

The parameters for calculating generally are determined by in situ test results, taking the mean values or weighted mean values. The shear strength of the sliding zone is the utmost factor for the calculation; therefore, the three methods of test, back analysis, and experienced analogy are applied to comprehensively determine them.

For the soil of the sliding zone below ground water level, the strength of the sliding zone is adopted to be the residual values of the consolidated-quick shearing tests where the water content is near the liquid limit. For that above of ground water level, the residual values of quick shearing test in natural water content are adopted.

For the recent reactivated landslides, such as the Xintan landslide and the Jibazi landslide, back analysis is adopted to presume the shearing strength. For the sliding mass without any specimens, parameters are chosen by comparing them with similar landslides.

Failure Probability Analysis

Failure probability analysis of the rock fall and landslide stability is characterized by Monte Carlo simulation analysis. The present study shows that c and φ values of the sliding zone are random variables obeying normal distributions, the factor of safety (K) being a certain function of c and φ is also a random variable. Using Monte Carlo analysis, a series of c and φ values are produced by simulation, and then the values are applied to the limit equilibrium method to obtain the factor of safety (K). Taking the probability of $K<1$ (the failure probability) and P as the index of the stability judgment, the criteria is suggested as $P<30\%$, stable; $P=30$–60%, basic stable; $P=60$–80%, poor stable; $P>80\%$, non-stable.

Sensitivity Analysis

Sensitivity analysis is the study of the sensitivity of a given parameter to the factor of safety by changing the one and keeping the others invariant in the stability calculation. This analysis not only can ascertain the controlling factors of the stability but also be a supplement to the limit equilibrium and failure probability analysis.

There are two methods for sensitivity analysis:

(1) *Sensitivity analysis for the singles*: The method was carried out for 33 large and medium landslides on the mainstream and 26 large ones on the tributaries. The approach is to select the representative sliding section for a landslide, using the Sarma method to calculate the relation between the factor of safety with the different water level of reservoir, ground water level, seismic intensity (6 or 7 degree) and sudden drawing down of the reservoir water level to flood control limitation level, and so on. Then considering the factors based on the mother rock properties, the granular composition and the water content variation of the sliding zone or potential sliding zone or through engineering geologic analogy zone, to evaluate the variation range of the shearing strength parameters (c, φ), finally judging the stability of the landslides under various constitution of conditions (Fig. 2.13).

(2) *Sensitivity analysis of the main area affecting factors for the large ones*: Analysis and assessment of the sensitivity of landslide stability to friction angle of the soil in the sliding zone, dip angle of sliding surface, slope of the landslide surface, sliding resistant ratio (ratio of the resistant length to the total length of the sliding surface), saturated thickness ratio (ratio of the mean thickness of saturated portion to that of total sliding mass), submerged ratio (ratio of the length of the sliding surface submerged underwater to that of the total sliding surface), and daily maximum rainfall suggest that sliding-resistant ratio, slope of the landslide surface, dip angle

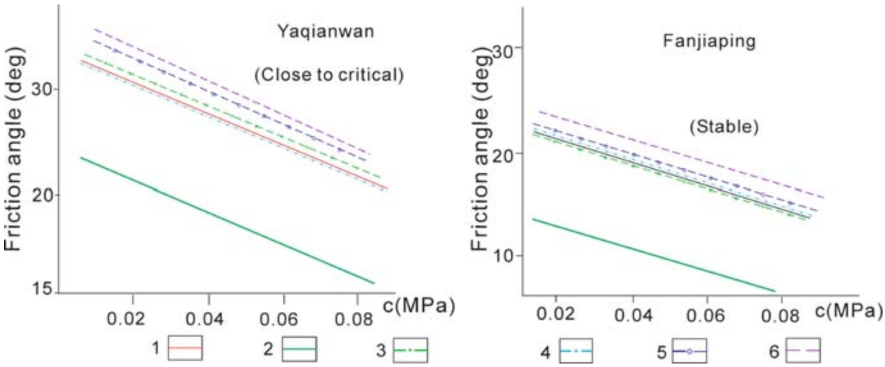

Fig. 2.13 Sensitivity analysis results of the landslide stability for two cases on the mainstream. 1 – Natural river water level, lower half portion of the slope saturated, 6 degree of seismic intensity; 2 – Natural river water level, no water in the slope, 6 degree of seismic intensity; 3 – Lower half portion of the slope saturated, 145 m reservoir water level, 6 degree of seismic intensity; 4 – Lower half portion of the slope saturated, 175 m reservoir water level, 6 degree of seismic intensity; 5 – Lower half portion of the slope saturated, 6 degree of seismic intensity, water level suddenly drawing down from 175 m to 145 m; 6 – Natural river water level, lower half portion of the slope saturated, 7 degree of seismic intensity

of sliding surface, submerged ratio, and friction angle are the most sensitive factors to landslide stability; daily maximum rainfall and saturated thickness ratio are the medium ones, and cohesion is the lowest one.

Fuzzy Comprehensive Evaluation

The 10 factors friction angle, impedance ratio, submerged ratio, saturated thickness ratio, dip angle of sliding surface, slope of landslide surface, active state, daily maximum rainfall, earthquake, and human activity were selected for fuzzy comprehensive evaluation. Consideration is given to not only the action of the internal and external dynamic agents but also the effect of the inner structures and outer morphology of the sliding mass.

For stability assessment of the landslides in the Three Gorges reservoir, the main approach is to use micro-geologic judgment. For the large and huge ones, various calculations and analysis methods were carried out. For a few potential unstable deforming rock masses which have been studied in detail (such as Lianziya dangerous rock mass, Huanglashi landslide), finite element simulation, discrete element simulation, and centrifugal model tests were applied. For the work mentioned above, stability of the landslides in the Three Gorges reservoir are divided into four degrees (a) stable, (b) fairly stable, (c) poor stability, and (d) unstable; the indicators for determining these categories are shown in Table 2.9.

After the comprehensive assessment of the 684 landslides with the size more than 100 thousand m^3 each in the mainstream and tributaries, in the natural state, it was found that there are 569 stable (a) or fairly stable (b) landslides with a total size of 262 million m^3, which accounts for 83.2% and 86.2% in number and in size of the total, respectively; 115 poor stability (c) and unstable (d) ones with a total size of 420 million m^3, accounted for 16.8% and 13.8% in number and size of the total, respectively. Of the landslides with size more than 1 million m^3; there were 64 of poor stability and unstable ones with the total size of 340 million m^3, accounted for 20% and 11.8% in number and in size of the total, respectively. All the huge ones and more than 85% large ones belong to the stable and fairly stable types in the reservoir area (Table 2.10). Therefore, stability of most landslides on the reservoir bank slopes is good or comparatively good.

Effect on the Rock Falls and Landslide by the Reservoir Impounding

After the Three Gorges reservoir begins impounding water, except for few landslides being either submerged totally or above the reservoir water level without the influence of the water fluctuation, most will be affected by variation of the water level. Effect on stability of the landslides by the water fluctuation depends on geographical position and the stability of the sliding mass, shape and elevation of the sliding surface, structure and material composition of the sliding mass, drainage condition of the slope, and the flood process of the reservoir. According to the three methods

Table 2.9 Criteria for stability classification of the landslides

Stability / Methods			Stable (a)	Fair stable (b)	Poor stable (c)	Non-stable (d)
Deformation and revival symptoms			No	No	No	Yes
Extensive activation recently			No	No	May be	May be
Macro-geologic judgment	Geography	Height difference between the front and the back	Little	Fairly little	Fairly large	Large
		Slope of landslide surface	Gentle	Fairly gentle	Fairly steep	Fairly steep
	Slope structure	Firm or cemented extent	Well	Better	Fairly poor	Fairly poor–poor
		Attitude and character of sliding surface	Gentle, high strength	Fairly gentle, reverse segment is short, high strength	Fairly steep or gentle, fairly low strength	Fairly steep or gentle, low strength
	Characters of the rear portion	Material distribution	Little	Fairly little	More	More
		Back cliff	Stable, no significant erosion	Basically stable	Possible collapse	Possible collapse or forming
		Collapse activity	No	No	May be	Has

Table 2.9 (continued)

Stability / Methods		Stable (a)	Fair stable (b)	Poor stable (c)	Non-stable (d)
Hydrogeologycondition	Water convergent area	Small	Fairly small	Fairly large	Fairly large
	Infiltration condition	poor	Fairly poor	Fairly well	Well
	Drainage condition	Gullies developed and deep cut, good drainage conditions	Gullies developed, good drainage conditions	Not smooth in local drainage system	Not smooth in total or local drainage
Calculated factor of stability (*K*)		High	Not high	Little higher than 1	$K \leq 1$
Sensitivity analysis		The landslides keep stable state when the affecting factors change to worse tendency.	The landslides close to critical state when the affecting factors change to worse tendency.	The landslide is in critical state when the affecting factors change to worse tendency.	The landslide is worse than critical state when the affecting factors change to worse tendency.
Failure probability (*P*)		$\leq 30\%$	30–60%	60–80%	$\geq 80\%$
Fuzzy evaluation		Stable	Basically stable tends to be stable	Basically stable, tends to be unstable potentially	Unstable or unstable potentially

Table 2.10 Stability classification of the landslides with the size more than 1 million m^3 in the Three Gorges reservoir (before storage)

River	Stability	1–10 million m^3 (medium)		10–100 million m^3 (large)		>100 million m^3 (huge)		Landslides
		No./size	Proportion to the total (%)	No./size	Proportion to the total (%)	No./size	Proportion to the total (%)	>1 million m^3
	Poor stable (d)	6/2,172	5.7/5.7	1/1,800	3.6/3.6			Huanglashi, Lianziya, Yaqianwan, Yutang, Qianxigou, Dongzi, Wangyemiao –. totally 7.
	Fairly poor stable (c)	6/2,129	5.7/5.5	4/9,213	14.3/10.5			Zuojituo, Xiangjiawan, Ciancaotuo, Yunyangxicheng, Taping, Huangguashu, Sandengzi, Mmiaoping, Lishupin, Biaoganshang – totally 10.
Mainstream	Basically stable (b)			5/19,380	17.9/22.2	1/12,933	33.2/29.2	Xintan, Huangtupo, Baiheping, Baihuanping, Baota, Jibazi, Shuping, Fanjiaping, Shuizhuyuan, Liujiawuchang, Baiyi'an, Xinwu, Outang, Guling, Jiuxianping, Yuhuangguan, Caojiezi, Anlesi, Taibaiya, Diaoyaping, Houzao, Maoxuzi, Longwangmiao, Chenjiadiaoyan, Caofang, Zhongangjiaolu, etc. – totally 119.
	Stable (a)	93/34,125	88.6/88.8	18/50,056	64.3/65.2	2/31,400	16.7/70.8	

Table 2.10 (continued)

River	Stability	1–10 million m^3 (medium)		10–100 million m^3 (large)		>100 million m^3 (huge)		Landslides
Tributaries	Poor stability (d)	7/1,796	4.4/3.6	1/2,394	4.0/4.5			Xiangshuitan, Hujiacitang, Tianmachi, Paotongwan, Nianziping, Mahuanggou, Huangnibaping, Dalinba – totally 8.
	Fairly poor stable (c)	37/11,961	23.4/24.3	2/2,959	8.0/5.6			Yinwozi, Pijiayuanzi, Xiangxi town, Bazimen, Baofutai, Xiangxihe Mineral Bureau, Zhnegjiahe Coal Mine, Zigui Cement Plant, Sangshuping, Dengjiawan, Xindatian, etc. – totally 39.
	Basically stable (b)	50/17,436	31.6/35.4	11/21,386	44/40.5	1/19,020	100/100	Shifosi, Wujiadaling, Hujiawuchangwu, Zhaizibao, Lianyuchi, Shijiawan, Longpo, Wangjiayuanzi, Zhoujiayuanzi, Wanbeituo, Yangjiaotan, Yanjiao town, etc. – totally 62.
	Stable (a)	64/18,076	40.5/36.7	11/26,019	44.0/49.3			Kaziwan, Dawuchang, Hualianshu, Baiwafang, Zhichang, Dashiban, Duoxiaoping, Panjiayuanzi, Wutongping, Oujiaping, Tukan, etc. – totally 75.

of the reservoir operation, effects of the reservoir on the landslides have the two aspects as below.

Effect of the Normal Water Level

After water storage, the hydrogeological condition of the submerged part of the landslide will be changed; especially, change of the physical and mechanical properties of the sliding zone directly influences the landslide stability. However, change of the sliding zone strength is related to the material composition, permeability, natural underground water level, and other factors.

Study on the typical and huge landslides shows that, except for a few strong permeability landslides, in natural states, the sliding zones or potential sliding zones of most landslides are totally or partially below ground water level annually, and apparently the rising of the reservoir water level has no essential effect on the strength. But strength of the portions above ground water level for the sliding zones and the sliding masses composed of soil with breccias will be decreased after saturation. This negative condition should be considered in sensitivity analysis of the landslide stability.

By analysis, comparing the factor of safety before to after storage for the 37 typical and large landslides as the reservoir water level reaches the 175 m level and whether the strength change of the sliding zone and sliding mass is ignored, it is equivalent or there is a little increase for 44% after storage, a little decrease for 24% (3–10% decrease in the factor of safety), and a large decrease for 32% (11–30% decrease in the factor of safety). But of the ones experiencing decrease, only two have the factor of safety near to 1.0, and the others are all above 1.08. As indicated, the normal reservoir water level has influence on the landslide stability.

Effect of the Reservoir Water Level Fluctuation

There are two periods of prominent fluctuation as the Three Gorges reservoir routinely operates:

(1) Slow falling of water level before the flood season. In the 5 months from November to March, the water level in front of the dam falls from a normal level 175 m to the flood control limit level 145 m, with a 30 m reduction in velocity of about 0.2 m/d. Comparing the bank slopes of the reservoir to bank slopes in other parts of the world, there is no apparent effect on the entire stability of the reservoir bank slopes under such decreasing velocity, but it may induce sliding failure of some deformable masses with poor stability.
(2) Rapid falling in a small range. This is sudden drawdown of reservoir water level after a peak flood in flood season. Magnitude of the drawdown range depends on the flood amount and flood type. Take the 1954 flood for instance, the maximum drawdown of the water level in front of the dam was 17 m with the velocity of 1.2 m/d. This kind of large range and rapid falling of water level resulted from

simultaneously appearing torrential rain, and flood will be the important factor for the failure of the poorly stable and unstable landslides.

After reservoir storage, the effect of water level fluctuation on stability of the landslide can be basically recognized by sensitivity analysis, stability calculation for typical landslides, and drawing and analogy to the Gezhouba reservoir. Sensitivity analysis was carried out for the 28 large landslides on the mainstream in the case of extreme drawdown of the water level, only 7 of them decreased in stability compared to their natural state. For the 31 large and huge landslides on the mainstream, by the methods of macro-geologic judgment, stability calculation, failure probability analysis, and fuzzy comprehensive evaluation, it is shown that only one (Longwangmiao landslide) degraded from class b to class c, and degraded another one (Anlesi landslide) from class a to class b. While for the others, it was the same as in their natural state.

Hazard Assessment for Failure of the Reservoir Bank Slopes

Analysis of the Main Factors Inducing Hazards

The damage intensity by the river bank slope failure depends on the size of the sliding mass sliding into the river and the surge it would be inducing. If the mass sliding into the river was larger, it could destroy houses, farmland, public transportation, and communication facility; and obstruct or even disrupt the navigation of Yangtze River. A high surge would cause different degrees of dangers to various buildings, public accommodations, and farmland.

Estimation of the Size Sliding into River

Exploration and research on stability of the bank slopes and landslides of the Three Gorges reservoir suggest that water storage basically will not change the present condition of the rocky bank slopes. Most of the landslides with relatively good stability would keep entirely stable except some small-scale collapses in the water level variation zone. Some poor or fairly poor stable ones may destabilize locally, and a few in the process of deforming may failure entirely. Scattered alluvial and deluvial bank slopes may collapse to reach a new equilibrium state under water immersion and scouring, but the size of the collapse may be small. Therefore estimation of the volume of the sliding mass into river was mainly carried out for the single unstable ones.

The eight poor and fairly poor stable landslides, including Lianziya and Huanglashi, were studies to estimate the size of the slide into river, using formula calculation and case analogy.

The size of lip mass sliding into river can be estimated by the following equation:

$$V_{\max} = \frac{S_{\max}}{L_{\max}} V$$

where

$V_{\max}$ – The maximum size of the sliding mass sliding into river (m^3);
$S_{\max}$ – The maximum average sliding distance of the landslide (m);
$L_{\max}$ – The maximum length of the landslide (m);
V – Total size of the sliding mass (m^3).

The Jibazi landslide in 1982 and the Xintan landslide in 1985 can be used as an analogy; as they slid into river, their size accounted for 1/8 and 1/11 of the total, respectively. The volumes of the material which slid into the river for the eight landslides are shown in Table 2.11.

Table 2.11 Estimation of the size of material sliding into the river for poor and fairly poor stable landslides on the mainstream of the Three Gorges reservoir

	The size sliding into river ($\times 10^4$ m^3)			
		Empirical value		
Landslide name	Calculated value	1/8 of the total size	1/11 of the total size	Note
Lianziya dangerous rock mass	216	216	216	Assume the segment facing to the river slides into river
Huanglashi landslide	427	225	163.60	The volume of the sliding mass in the west part is considered as $1{,}800 \times 10^4$ m^3
Xiangjiawan landslide	127.49	250	181.82	
Yaqianwan rock fall	41.97	81.25	59	
Qiancaotuo landslide	271	420	305.45	
Sandengzi landslide	94.61	86.38	62.82	
Yuanyangxichen landslide	100.06	312.50	227.27	
Longwangmiao landslide	269.13	126.88	92.27	

Estimation of the Surge

Here, some methods for estimation of the height of the surge by landslides are applied for the Three Gorge Project.

Table 2.12 The results of the surge test for the Xintan landslide

Times	Test conditions				Surge height in front of the dam
	Reservoir water level	The sliding size into water	Sliding velocity (m/s)	Flood discharge ($\times 10^4 m^3/s$)	
1	150	1,600	41.4	3	0.63
2	150	500	64.5	3	0.50
		1,600			1.00
3	130	500	67.5	3	0.75
		1,600			1.50
4	95	500	72.4	1.6	0.75
		1,600			1.38

(1) *By surge test*: Yangtze Scientific Research Institute used the hydraulic model for the head segment of the reservoir and selected a huge landslide (the Xintan landslide) and a dangerous rock mass (Lianziya) which are close to the dam and have poor stability at the time of the surge tests under different failure conditions, sliding sizes, and water levels. The results for the Xintan landslide are shown in Table 2.12.

It was found that the surge attenuation is influenced by the river, prominently. If the river has more meanders, tributaries, and brooks, it is favorable to the surge attenuation. It is especially evident in the upstream passing mender V-shape gorge, as the height of the surge attenuated rapidly. The surge height of the Xintan landslide was only 1.5 m up to the dam site when using the extreme conditions of the maximum sliding size and the highest sliding velocity for testing.

(2) *By surge calculation*: Calculated results using various formulas were compared to the real measured value of the 1985 Xintan landslide, and it is concluded that the method of the U.S. Corps of Civil Engineers is suitable to the characteristics of the Three Gorges reservoir. This method assumes that the sliding mass is emerged in a semi-infinite water body and the vertical falling distance is bigger than the water depth. Using a theory of gravity in a linear relation to the surface area, a calculation formula for surge height induced by landslide is derived. Supposing the eight poor and fairly poor stable landslides along the reservoir bank slopes had failed, the surge heights induced by them at the entry point (the opposite bank slope) Sandouping dam site and town nearby were calculated.

(3) *By case analogy*: The Xintan landslide, in June 1985, had 3.4 million m^3 of material sliding into the Yangtze River instantaneously. The surge reached 49 m in height at the entry point of the opposite bank slope, but it attenuated up and down the river rapidly. At 1 km downstream in the river, the surge height was 7 m, at 7.5 km was 2 m, at 11 km was 0.5 km, and no effect at the dam site. In the up-river, the surge height was 5 m at 4 km (Xiangxi town), and only 10 cm at 13 km (Zigui county) (Fig. 2.14).Other cases of landslides with surge-height measuring data also can be referred to.

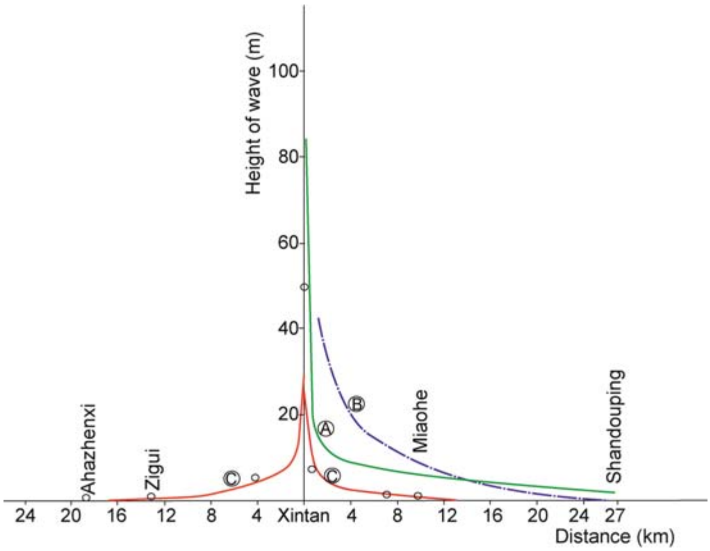

Fig. 2.14 The attenuation curve of surge height for the Xintan landslide. A – Calculated attenuation curve, size into river 16 million m^3, velocity into water 100 m/s, water level 150 m; B – tested size into river 16 million m^3, velocity into water 67 m/s, water level 130 m; C – measured attenuation curve on June 12, 1985 sliding

Analysis and Assessment for Potential Harm

Influence on Storage Capacity and Lifespan of the Reservoir

Comparing the size of rock and soil possibly sliding into the reservoir during bank slope failure with the total storage size, the intensity that the landslide deformation and failure have on the reservoir storage capacity can be evaluated.

The total size of the 684 landslides with each size larger than 100 thousand m^3 distributing along the three gorges reservoir is 3.04 billion m^3, even if they all failed and 1/8 of the total size slipped into river, the size into the water only accounted for 1% of the total water storage, and 2% of the dead water storage. Therefore, the landslides have no substantive influence to the storage capacity and lifetime of the reservoir if failure were to occur.

Influence on Construction and Operation of the Key Structures

The influence of reservoir bank slope failure on construction and operation of the key structures includes two aspects of direct and indirect influences.

(1) *Direct influence*: After years of detailed investigation, it is suggested that the front area of the dam is low hills and gentle slopes composed of crystalline rocks, neither large landslides nor the terrains, and geological conditions preferring large

landslides. There are no unstable bank slopes or landslides in the head segment of the reservoir directly threatening the stability of the key structures.

(2) *Indirect influence*: Neither poor nor fairly poor stable large and huge landslides exists; also, the geological conditions characterizing the landslides within 26 km long up river from the dam do not exist. Therefore, only the influence of the surge produced by unstable landslides 26 km away from the dam should be considered.

Poorly stable and deforming Lianziya dangerous rock mass and Xintan landslide, which are possible local failures, are 26–27 km away from the dam. Xintan landslide failed in 1985; the surge it produced attenuated rapidly downstream and basically vanished up to the dam site. In the future operational period, the possibility of the landslide reactivating as in 1985 is minor. But in the surge study, several conditions worse than those in 1985 sliding are assumed to be possible according to surge test and calculation, but the result represented that the highest surge up to the dam is only 2.7 m.

For Lianziya dangerous rock mass, supposing 2.16 million m^3 rock mass adjacent the river fell into the river at once, calculating the various schemes and with different methods, the surge heights up to the dam are all less than 2.0 m. Other landslides which may fail are all 65 km away from the dam site. Once they would fail and slip into the reservoir, the surge height up to the dam would be lower than above-documented ones. Thus surge caused by reservoir bank slope failure will not affect the construction and safety of the key structures.

Influence on Navigation

Influence on Navigation Before the Dam Was Built

In history, there were about 140 rapids in the Three Gorges reservoir segment, and investigation suggests that many of them were formed by landslides occurring in past history. After the Gezhouba reservoir storage, all the rapids down from Fengjie county were merged, in addition to many years of regulation; the shipping conditions of the channel had apparently been improved. But the conditions of the river bank slopes were not changed basically, the capability of controlling the failure of landslide to obstruct the navigation is still weak, and once a large landslide broken, it may result in serious navigation obstruction. Take 1982 Jipazi landslide for instance, where 2.3 million m^3 soil and rock masses slipped into the river, making the river bed experience uplift 30–40 m high. Most river section for navigation was occupied and the navigation was once obstructed. It has recovered after a large amount of regulation work. As to the Xintan landslide in 1985, 2.6 million m^3 soil and rock masses accumulated under water, extending forward into the river, 90 m wide and which occupied one third of the water area of the river section below the water level of 65 m (Gezhouba reservoir normal water level). Accounting for the river dry water level, it occupied about two thirds of the river section below water (Fig. 2.15). If Gezhouba reservoir had not raised the water level 20 m above the dry level, it might have lead to serious navigation obstruction.

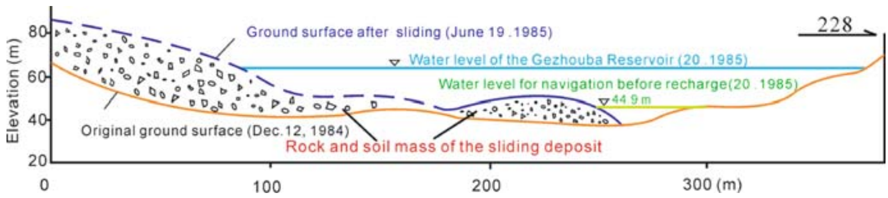

Fig. 2.15 Contrast of the channel sections before and after the Xintan landslide occurred

Referring to the above cases, without the Three Gorges reservoir, if the large or huge landslide with poor or fairly poor stability was a failure and only 1/8 and 1/11 of the total sliding mass slipped into the river, the soil and rock masses would occupy 50% of the river section under dry water level (Table 2.13), which would result in a serious navigation obstruction.

Effects by the Reservoir, to Navigation

As the reservoir formed, it will deepen the water depth 10 to 100 m, widen the water surface 200 to 800 m, increase the water area of the cross section 3–5 times. The possible size of the sliding masses sliding into the reservoir by failure of the poor and fairly poor landslides is generally thought to be 400–750 thousand m^3, at the most, about 4 million m^3. Considering the lowest reservoir water level, that is flood control limitation level, 135 m (earlier) and 145 m (latter), the area that the sliding masses occupied in serious segment takes up just 30% of the total water area of the cross section under water (Table 2.13). The rest of the area is far more than the area of the river section before the reservoir was built, so it basically does not affect the safety of the shipping channel. Therefore, the reservoir itself essentially mitigates the harmful effects of large and huge landslides to navigation.

Effects to Towns and Immigrant Settlement in the Reservoir Area

Most landslides along the reservoir bank slopes often are the main places for people to labor and live. In a natural state, because of natural agents and human activities, some deformation and unstable landslides have caused hazards to cities and public centers to some extent, and the old Xintan town was destroyed at a glance. Yunyang, Wanxian, Changshou, Xiangxi, etc. towns and cities have buildings damaged in different degree by landsliding and deformation after the Three Gorges reservoir was constructed, and the present deforming landslides may tend to aggravate the situation and would seriously destroy the buildings that are located.

Table 2.13 The volumes of the sliding mass accumulating under the water as the several large landslides in the Three Gorges reservoir were supposed failure entirely

	Percentage of the area soil and rock masses occupied under water to the original area under water in the river cross-section							
	1/11 of the total in size into the water				1/8 of the total in size into the water			
Landslide name	Natural dry water level	135 m level	145 m level	175 m level	Natural dry water level	135 m level	145 m level	175 m level
Lianziya	88.1	31.5	28.5	20.0				
Huanglashi	48.3	11.3	9.9	6.5	65.5	15.4	13.5	8.8
Yaqianwan	82.6	9.1	7.4	4.7	113.0	12.4	10.0	6.6
Xintan	88.1	5.6	5.0	3.6	163.3	7.8	7.0	5.0
Zuojituo	34.0	15.0	12.9	7.8	46.0	20.3	17.4	10.6
Xiangjiawan	144.0	17.8	14.9	9.1	200.0	24.7	20.7	12.6
Qiancaotuo	155.0	15.8	132	8.4	212.0	21.6	18.1	11.5
Sandengzi	43.3	9.4	7.7	4.8	58.3	12.6	10.3	6.4
Baota	103.0	24.3	20.4	13.1	139.0	32.9	27.6	17.8
Yunyangxicheng	35.2	7.4	6.0	3.6	48.1	10.2	8.3	5.0

Note: Lianziya accounted for the 216 thousand m^3 adjacent to the river.

Table 2.14 Calculation result for the surge height caused by the landslides on the mainstream of the Three Gorges reservoir

Landslide name and location	Affected place	Distance (km)	Surge height (the highest surge on the opposite bank slope (m)/surge height in the affected place (m)					
			1/8 sliding into the reservoir			1/11 sliding into the reservoir		
			Previous river water level	135 m level	175 m level	Previous river water level	135 m level	175 m level
Xintan, Zigui	Sandouping dam site	27	>40/0.9–1.8	>40/0.89–1.6	>40/<1.5	40–59.5	40–45.9/	40.2/<1.2
Lianziya, Zigui	Sandouping dam site	27	>40/0.6–2	31–81.3/<0.7	23–70/0.6–2			
Daping, Badong	Badong county	5	45–63.1/2.3–4	25–42.3/1.5	13–32/0.9–3	39/1.9	22/1.3	11/1.0
Huanglashi, Badong	Badong county	1. 5	50–71/7.5–11.8	20–44.8/0.7	33–65/4–9.5	50/10	38–50/8.7	33–50/8.1
Zuojituo, Badong	Badong county	17	35–>58/1–1.5	49–61/1.4	9.8–38/0.4–1	30.5/0.9	17/0.6	8.4/0.4
Caojiawan, Wushan	Wushan county	9	>50/1.5–1.8	49–61/1.4	35–50/1–1.1	>50/1–1.5	41/1.2	30/<1.0
Yaqianwan, Wushan	Wushan country	10	48–57.1	40–50/1.1	34–41/0.9–1	42–1.1	34/0.9	29/0.8
Yaqianwan, Wushan	Wushan county	9	41–54.7/1.1–2	20–42.8/0.6	9.7–37/0.4–1.5	33–0.9	16/0.5	8/0.3
Qiancaotuo, Fengjie	Fengjie county	5	48–57/1.4–3	25–44/1.2	8.4–38/0.6–2	41/1.2	21.6/1.0	7.1/0.5
Qiancaotuo, Fengjie	Fengjie county	12	42–50/1–1.5	31–60.4/0.9	22–53/0.7–1.2	34/0.9	26/0.7	19/0.4
Sandengzi, Fengjie	Yunyang county	>20	2.8/<0.2	1.9/<0.1	0.7/<0.1	2.4/<0.1	1.6/<0.1	0.6/<0.1
Lieloushan, Fengjie	Yunyang county	>20	17.5/0.7	14/0.6	10/0.5	15/0.6	12/0.5	8/0.4
Dongzi, Wanxian	Wanxian city	10	8.8/0.3	8.2/0.3	4/<0.2	7.5/<0.3	6.9/0.2	3.4/0.1
Wangyemiao, Fuling	Changshou county	10	8/0.3	7.4/0.2	3.6/<0.2	0.8/0.2	6.3/0.2	3/0.1

In addition, analysis and calculation (Table 2.14) suggested that the surge produced by the poorly stable landslide sliding into the reservoir is also an indirect threat to the towns and cities nearby, especially the surge produced by extensive sliding of the Huanglashi landslide close to Badong county. It can reach to 8–10 m high, and this factor should be considered in planning the new buildings in a new town.

Monitoring, Prediction, and Mitigation for the Main Landslides

Deformation Monitoring and Prediction for the Main Landslides

Monitoring of poor stable and deforming landslides is an available measure to forecast the failure exactly. For example, Xintan landslide failed in 1985 and the failure was successfully forecasted, which averted huge loss of lives and properties. The success is attributed to the 7 years of ground deformation monitoring. Systematic monitoring for the poor and fairly poorly stable landslides in the Three Gorges reservoir can provide an important base for failure prediction and control measures. At present, a deformation-monitoring network has been set up for the Xintan, Huanglashi, Jibazi, and Douyapeng landslides and the Lianziya dangerous rock mass. In cooperation with the new immigrants of the urban relocation of the reservoir area, an automatic monitoring system is going to be constructed all over the reservoir area.

There is a quite long process before a landslide failure, including appearance and extension of the surface fissures, formation and transfixion of the sliding surface, cracking and falling of the dangerous rock masses, etc. Therefore, the deformation monitoring commonly includes two aspects of ground monitoring and underground monitoring.

Ground Deformation Monitoring

The general methods for ground deformation monitoring are high precise triangulation network and collimation line method. Xintan, Huanglashi landslides, Lianziya dangerous rock mass, and Douyapeng deformed body were adapted to these methods of monitoring the ground deformation.

On the Xintan landslide before 1977, five collimation lines termed A, B, C, D, E parallel to the Yangtze River were set up on the sliding mass in the area between the attitude of 600 m and the riverside, of which, each line was composed of five points, and the endpoints were put on firm bedrock, and others were set in a line on the sliding mass. With deformation, part collimations became invalid, so another eight intersection monitoring points were added on the attitude of 600–900 m, a coffin corner monitoring network composed of seven stationary points on the outer margin of the landslide bedrock was constructed. Systematic and reliable data were collected for many years by monitoring, which provided the evidence for exact forecasting. This method is high in precision, simple in operation, and convenient for determining the displacement quickly. Monitoring of the vertical displacement was adapted to second-class level to make the measuring accuracy.

Comprehensive Survey Bureau, Yangtze River Committee used GPS to monitor the ground deformation of Baota (Jibazi) landslide in Yunyang county and Xiakouzhen landslide in Xingshan county, etc.

Besides monitoring for the deformation of the entire sliding mass, the relative displacement among the blocks on and below the surface of the sliding mass also should be monitored. As the case with Lianziya dangerous rock mass, 21 observational standard piers were set up at different blocks divided by cracks, and high-precision triangle measuring and second-class angle precision anterior intersection method were allied to record the displacement of each rock block. More than 30 relative displacement observation points were set up on the ground and in the cracks of the dangerous rock mass, and a crack meter extension rod, dial indicator, Spiral micrometer, precise level bubble, etc. were applied to measure the relative opening, closure, and vertical movement between blocks.

Deep Deformation Monitoring

Deep deformation monitoring is mainly used to determine the position and deformation characteristics of the sliding surface. At present, the most useful and comparatively economical apparatus is a borehole inclinometer. It is used for monitoring in Huanglashi landslide, and valuable data like the depth and displacement of the sliding surface, the correlation between displacement and rainfall, river water level, etc. were obtained (Fig. 2.16). Many borehole inclinometers were set up on Taibaiya, Anlesi, and Douyapeng landslides and on a deforming rock mass in Wanxian city to obtain fairly good observation data.

In addition, if conditions permitted, a tunnel could be excavated up to the sliding surface and high precise short-survey crosses could be set on the sliding surface to measure the relative displacement. The method was used on the Huanglashi landslide and it achieved a good effect. For deep monitoring in the Xintan landside, an F-12 style dislocation meter was used to monitor the relative displacement in the creep stage; a WL-30 pressure gauge was used to monitor the stress variation in the deep position; multi-points plumb, dislocation meter, adhesive wall-adhesive displacement meter, and crack needle installed on the shaft wall were used to measure the displacements of the sliding zone and sliding mass at different locations and depths.

Coordinating the monitoring of the landslide deformation, other items such as hydrology, meteorology, earthquake, and hydrogeology should also be observed simultaneously, as these data are significant in forecasting the deformation and development of landslides.

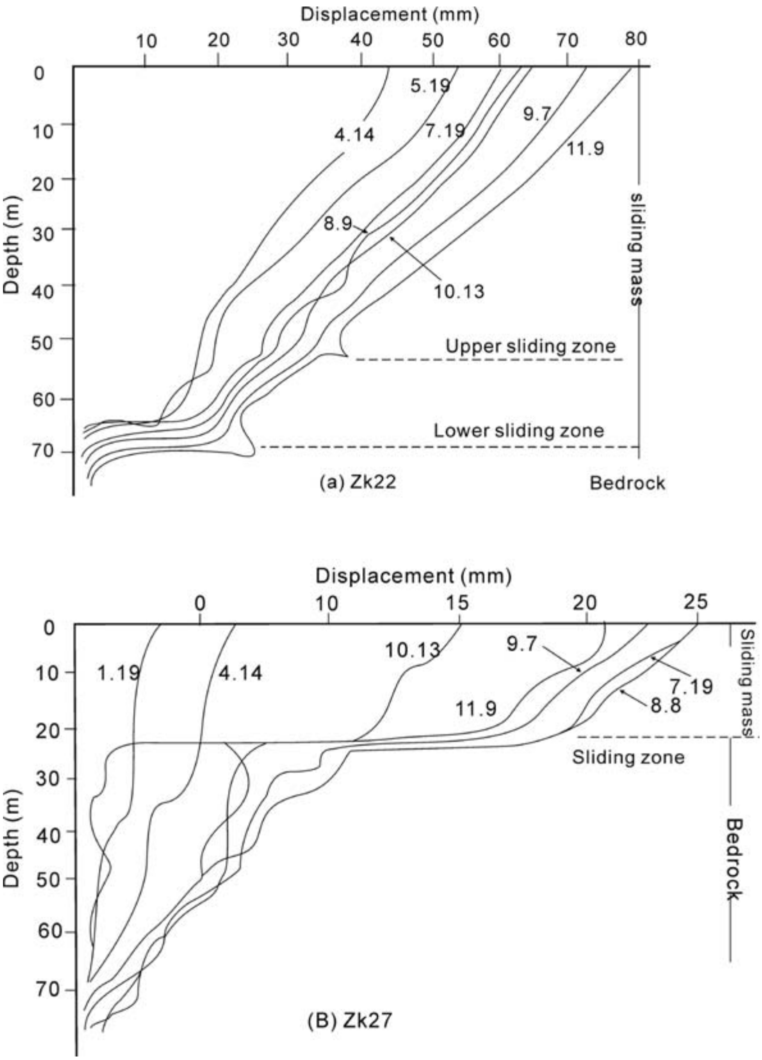

Fig. 2.16 The curves of displacement verses depth measured by borehole inclinometers in the Huanglashi landslide

Prediction

The aim of monitoring a landslide is to forecast its deformation and failure correctly and to make a decision for mitigation. The deformation process of a typical landslide can be divided into four stages. The initial stage is slow deformation, the following stage is apparent deformation, in this period, deformation trace can be seen on the ground, such as ground fissures, building cracks and incline, and these two stages last for a long time. The third stage is accelerating deformation, not only the

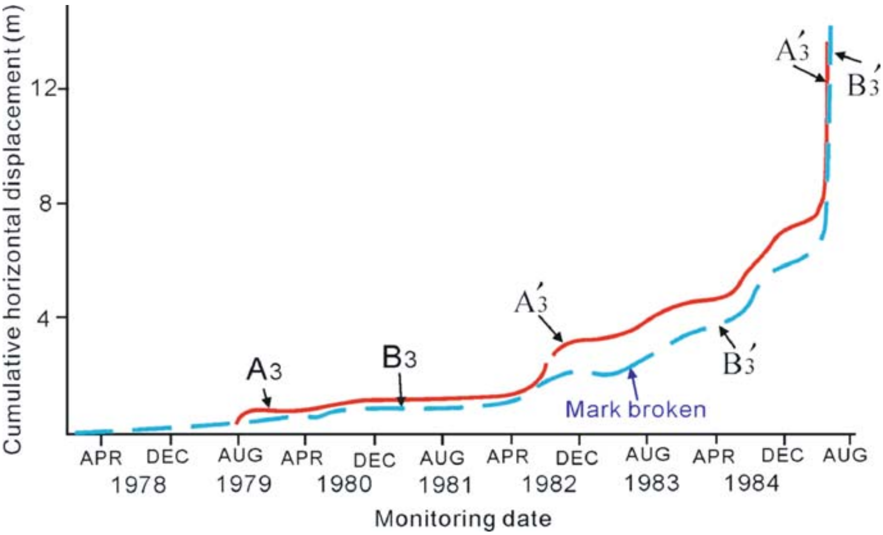

Fig. 2.17 Cumulative horizontal displacement curves on the observation lines A3-A3′ and B3-B3′ for the Xintan landslide

amount but also the velocity of the deformation increases with time. The last stage is failure of the landslide. Corresponding to deformation stages above, prediction of landslide failure can be divided into early prediction, medium-term prediction, short-term prediction, and critical sliding prediction. For example, the forecast for the Xintan landslide, before 1979 belongs to the category of early prediction, from 1979 to 1981 is medium-term prediction, from 1981 to 1984 is short-term prediction, and the critical sliding prediction started from March, 1985 (Fig. 2.17).

Treatment of the Landslides

The deforming hazardous landslides and dangerous rock masses should have measures taken to stabilize them. The design for stabilizing works should be based on the detailed investigation to pinpoint the main factors affecting the landslide stability and to avoid blindness. The main engineering mitigation measures include the following.

Water Drainage

The surface and the underground water usually are important factors affecting landslide stability, as most landslides happen in the rainfall period. Deformation monitoring shows that the majority of landslide deformation increases in the rainy season. Therefore, fixing the surface and underground drainage system is an important measure for enhancing landslide stability. For the Huanglashi landslide (Dashiban), for example, the factor of safety decreases by 0.005–0.07 when underground water level rises every 0.1H (H is the water thickness within the sliding mass). Both the Huanglashi and the Jibazi landslides utilized valid drainage systems and the results are fairly good.

Unloading

For the landslide having much source material from the back and with down thrusting failure type, unloading on the top area is advisable to reduce the down sliding force and to enhance the stability.

Anchoring and Retaining

Generally, anchoring is applied to the reinforcement of dangerous rock masses and the stabilizing of small landslides. Reinforced structures are usually retaining walls and stabilizing piles to enhance landslide stability. In addition, under certain conditions (such as when the rock mass up and under the slip is fairly intact), resistant bolts crossing the sliding surface or other measures can be applied.

Multiple treatment measures were adopted for the reinforcement of Lianziya dangerous rock mass, which included surface water drainage ditches, local unloading, reinforcing by stabilizing piles for local shallow sliding, and pre-stressed anchor cables for the dangerous rock mass facing the river. Especially effective is a series of concrete bolts on the bottom of the dangerous rock mass to keep the mass from entirely settling and sliding.