

Chapter 1

Geo-hazard Initiation and Assessment in the Three Gorges Reservoir

Chuanzheng Liu, Yanhui Liu, Mingsheng Wen, Tiefeng Li, Jianfa Lian,
and Shengwu Qin

Abstract Geo-hazard study results for the Three Gorges reservoir of Yangtze River are presented at three geographical scales: first, at the largest scale, is the geo-hazard investigation and evaluation of the whole reservoir area, which involves 19 counties (54462 km²); secondly, at a mid-level scale, is the initiation mechanism of complex slopes (landslides) in the Three Gorges section of the Yangtze River (about 4000 km²); lastly, at the small scale, research on the fan-shaped slope of Badong county new town was studied to ascertain its geologic characteristics, landslide initiation factors, and geo-environmental quality.

Keywords The Three Gorges reservoir of the Yangtze River · China · Geo-hazards · Landslides · Badong slope system · Gravity initiation · Geo-environmental quality

Introduction

Since the 1990s, we have been studying the geo-hazards of the Three Gorges reservoir on the Yangtze River and obtained scientific data for three geographic levels of scale, the largest of which consists of the whole Three Gorges reservoir encompassing 19 counties. At the mid-level scale, the Three Gorges segment of the reservoir was studied, and at a smaller scale, the slope stability evaluation for the New town of Badong County is presented.

Regional Assessments of Geo-hazards

Based on the compiled analyses of the existing papers and literature about mitigation of geological hazards (Aleotti & Chowdhury 1999, Carrara 1983, Haruyama & Kitamura 1984, Yin & Yan 1987, Baeza & Corominas 1996, Carrara et al. 1992,

C. Liu (✉)

China Institute for Geo-Environmental Monitoring, Beijing 100081, China
e-mail: liucz@mail.cigem.gov.cn

Aleotti et al. 2000, Michael-Leiba 2000, Ragozin 2000, Elliott & Gori 2000), the authors have set up a new assessment system for regional geological hazards.

Problems and Concepts

Basic Problems

The assessment for regional geological hazards addresses four basic problems as follows:

- (1) The status of geological hazards at present, which reflects types, quantity, distributive area, and space volume;
- (2) A correct description of geological environments as they relate to geological hazards which consists of landforms, morphological features, vegetation forms and degree of coverage, elements and structure of geologic bodies, groundwater distribution, and the dynamic background in relation to the earth's regional crust;
- (3) Evaluation of the potential geological hazards induced by various kinds of triggering factors, such as rainfall, earthquake, and all forms of human activity;
- (4) How to mitigate geological disasters which include impacts on human, property, infrastructure projects, and the living environment.

Basic Concepts

Four basic concepts are put forth, which include “distribution degree,” “potentiality degree,” “dangerous degree,” and “harmful degree” of regional geo-hazards as they relate to the above four problems (Liu & Yang 2001, Liu et al. 2004a).

Concept 1 “distribution degree” of geological hazards is a reflection of the development of geological disasters in the region which involves the numerical distribution, the area distribution, and the size distribution of geological hazards.

Concept 2 “potentiality degree” of geological hazards is an evaluative parameter that describes conditions using a combination of geo-environmental aspects.

Concept 3 “dangerous degree” for geological hazards expresses a quantitative possibility that occurs in a certain period of time due to some kind of triggering factors (natural or human made). In certain situations, “dangerous degree” can be used as an early warning index for levels of geological hazards.

Concept 4 “harmful degree” of geological hazards reflects a result that results in casualties, economic loss, and environmental destruction. It can be used as a basis to set up a disaster prevention and mitigation plan for a region.

Evaluation Method for Geological Hazards Regional Analysis

A regional geological hazards evaluation framework can be established by applying the analyses of “distribution degree,” “potentiality degree,” “dangerous degree,” and “harmful degree” (Liu et al. 2004a).

“Distribution Degree” of Geological Hazards

“Distribution degree” of geological hazards is the function of regional disaster frequency (f), area (s), and volume (v):

$$F = f(f, s, v) \quad (1.1)$$

In order to reflect the actual situation of the establishment of geological hazard “distribution degree” computational model, the first aspect of nondimensional treatment or normalization for the above-mentioned three indicators is applied.

1. *Disaster frequency ratio*: To set up unit i for the regional disaster frequency f_i , cell area of S_i , the frequency of disaster unit density ρ_{fi} ; the entire study area with an area of S , the total number of disasters for the f , the frequency of the total density of ρ_f , then

The i unit disaster frequency ratio

$$\begin{aligned} R_{fi} &= \rho_{fi} / \rho_f \\ \rho_{fi} &= f_i / S_i; \quad \rho_f = f / S \end{aligned}$$

2. *Geological hazard area modulus ratio*: To set up unit i with an area of the distribution of disaster— s_i , unit area of S_i , within unit i the disaster area modulus ρ_{si} ; the entire study area for the S , at a total area of disaster s , with a total area of module for ρ_s , then

Unit i area modulus ratio

$$\begin{aligned} R_{si} &= \rho_{si} / \rho_s \\ \rho_{si} &= s_i / S_i; \quad \rho_s = s / S \end{aligned}$$

3. *Geological hazard volume modulus ratio*: To set up unit i of the total volume for the disaster point v_i , unit area of S_i , i unit the size of the disaster modulus ρ_{vi} ; the entire study area has a total area of S , the total volume for the disaster point v , the total volume modulus ρ_v , then

Unit i volume modulus ratio R_{vi}

$$\begin{aligned} R_{vi} &= \rho_{vi} / \rho_v \\ \rho_{vi} &= v_i / S_i; \quad \rho_v = v / S \end{aligned}$$

So, (1.1) changes to

$$F_i = f(R_{fi}, R_{si}, R_{vi}) \quad (1.2)$$

R_{fi} , R_{si} , and R_{vi} are “distribution factors.”

A general equation (1.3) can be established by the practice of combining a large number of geological disasters in the Three Gorges reservoir area and comprehensive studies.

$$F_i = R_{fi} + R_{si}^{\frac{1}{2}} + R_{vi}^{\frac{1}{3}} + r \quad (1.3)$$

F_i – “distribution degree” of unit i ;

R_{fi} – Disaster frequency ratio of unit i ;

- R_{si} – Geological hazard area modulus ratio of unit i ;
 R_{vi} – Geological hazard volume modulus ratio of unit i ;
 r – Amended index, generally 1.5–2.0.

Because of the omission or too much emphasis on “people-oriented” aspects, the regional investigations of geological hazards could lead to many parts of the disaster that were not investigated, which are the “blind spots” or the “out area.” The Eq. (1.3) was amended in order to make up for the “blind spot” defects. Taking into account regional disaster points higher than the harm caused by the size and volume, consideration was given to the role of the three amendments to increase the amended index of r .

“Potentiality Degree” of Geological Hazards

“Potentiality degree” is the basis of various geological disaster trends such as early warning, and it can provide the basic indicators to a single or a combination early warning. Specific value calculation is based on the development factor and basic factor.

Equation can be written as:

$$Q = (q_1, q_2, q_3, \dots, q_n) \quad (1.4)$$

$q_1, q_2, q_3, \dots, q_n$ are the values of reflection of potential geological hazards.

For composite index model, (1.4) can be written in style:

$$Q_i = \sum_{j=1}^n a_j b_j \quad (1.5)$$

$i = 1, 2, \dots, m; j = 1, 2, \dots, n;$

Q_i – “potentiality degree” of unit i ;

j – evaluation factor;

a_i – assignment of j factor in unit i ;

b_j – weight of evaluation factor j ;

m – number of evaluation units;

n – number of evaluation factors.

The portfolio of geo-environmental elements is basic factors, including the frequency ratio, area modulus ratio, and volume modulus ratio and are integral parts of the basic factors as a response of the potential. Because it is a response of the potential and also can reflect the fragility of the geological environment, the “development factor” is also known as the “response factor.”

“Dangerous Degree” of Geological Hazards

“Dangerous degree” is calculated based on analysis of “potentiality degree,” then the trigger factors are considered, and the mathematical model becomes consistent with the “potentiality degree” computing model.

Using the composite index model,

$$W_i = \sum_{j=1}^p a_i b_j \tag{1.6}$$

- $i = 1, 2, \dots, m; j = 1, 2, \dots, p;$
- W_i – “dangerous degree” of unit i ;
- j – evaluation factor;
- a_i – assignment of j factor in unit i ;
- b_j – weight of evaluation factor j ;
- m – number of evaluation units;
- p – number of evaluation factors.

According to actual data of the regional geological hazards investigation and experience, discriminate factors of “dangerous degree” calculation are divided into three categories: basic factor, response factor, and trigger factor. The assignment of trigger factor is based on the geological hazard history of the study area, especially the statistical analysis of the different factors that lead to different sections of the failure threshold range. Calculated “dangerous degree” can be used as an early warning indicator when a numerical trigger factor is known.

“Harmful Degree” of Geological Hazards

“Harmful degree” of geological hazards is the social attributes expressions of geological hazards. Focus on the “harmful degree” and the vulnerability of human life and property in disaster-stricken areas, and quantitative indicators, shows the expression as follows:

$$R = R(r_1, r_2, r_3, \dots, r_n) \tag{1.7}$$

$r_1, r_2, r_3, \dots, r_n$, where r_n is the value of the reflection of geological hazards.

In general, the damage from geological hazards is expressed as the casualties, the loss of the value, and environmental damage effects that cannot be measured by currency. “Harmful degree” is written in the general model of evaluation unit:

$$R_i = W_i \times V_i \tag{1.8}$$

- R_i – Unit harmful degree;
- W_i – Unit dangerous degree;
- V_i – Unit disaster–vulnerability index.

$$V_i = \omega_1 V_{1i} + \omega_2 V_{2i} + \omega_3 V_{3i} + \dots + \omega_n V_{ni}$$

$V_{1i}, V_{2i}, V_{3i}, \dots, V_{ni}$ are the indicators of vulnerability of all types of body; $\omega_1, \omega_2, \omega_3, \dots, \omega_n$ are the respective weights.

The Division Methods of Geological Hazard Evaluation

The results of regional geological hazard evaluation are classified from low to high. First, we chose a number of selected units (box, natural search or district) based on a general scale evaluation, calculation of the unit with a set of quantitative factors (quantitative), combining the unit which results in a number close to the value of its kind, that is, the map Merger spot – the traditional clustering method, based on the space adjacent to the clustering coefficient and so on.

This method is repeated until the objective of the work is reached. The idea is that the different levels of units are compared to a different factor in the working process and it uses quantitative expression if possible.

This study uses the combined method of spot map, according to the calculations of “distribution degree,” “potentiality degree,” “dangerous degree,” and the “harmful degree”, and it combines the units which are adjacent or close to the same level, forming the corresponding zoning map.

Evaluation of Geological Disasters in the Three Gorges Reservoir Area

The survey of geological disasters in the Three Gorges reservoir comprises an area encompassing longitude 106° – 111° , latitude 29° – $31^{\circ}21'$. The administrative divisions are those that occur across the 19 counties (districts) of Chongqing Municipality and Hubei Province, including the Yichang, Xingshan, Zigui and Badong counties in Hubei Province, Wushan, Wuxi, Fengjie, Yunyang, Wanzhou, Kaixian, Zhongxian, Shizhu, Yubei, Banan, Chongqing city urban area, Changshou, Fengdu, Fuling, and Wulong counties or districts in Chongqing Municipality, and the total area of the comprehensive investigation assessment is about 54462 km² (Fig. 1.1).

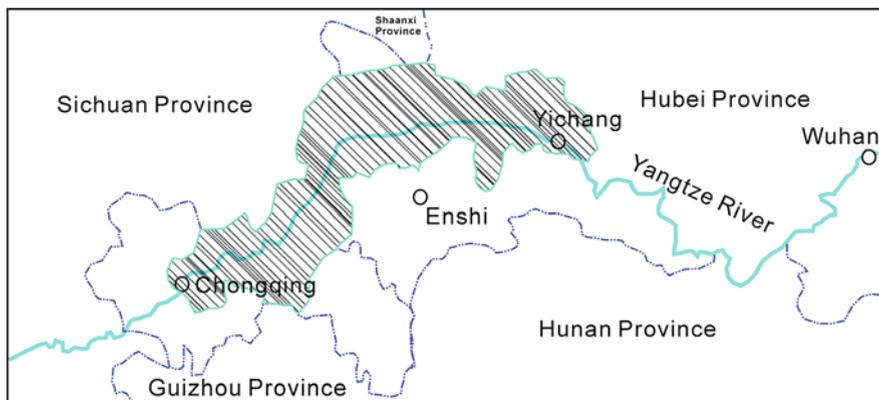


Fig. 1.1 Geo-hazard survey location of the Three Gorges reservoir region on the Yangtze River

Overall Features of Geological Disasters

The main targets of assessing geological disasters in the Three Gorges reservoir area survey are landslide and collapse, the perilous rock masses (unstable slope or deformed slope), debris flows, ground collapse, and cracking and collapse of reservoir banks. The scale of the investigation is 1:100,000 and a map in scale of 1:50,000 was used.

There are 7,068 points in the actual survey of geological disasters in the Three Gorges reservoir area; 5,706 points were found and registered, including 3,830 landslides, accounting for 67% of the total; landslides numbering 549, accounting for 9.6% of the total; 90 mudslides, accounting for 1.6% of the total; 85 incidences of ground collapse, accounting for 1.5%, 45 areas showing cracks, accounting for 1%; and 1107 unstable slopes, accounting for 19.3% of the total. The largest number of existing geological disasters is minimal, composed of 5,706 points, 3,658 were registered, accounting for 64.11%; and 93 points are giant geological disasters, which are 1.6% of the total number (Fig. 1.2).

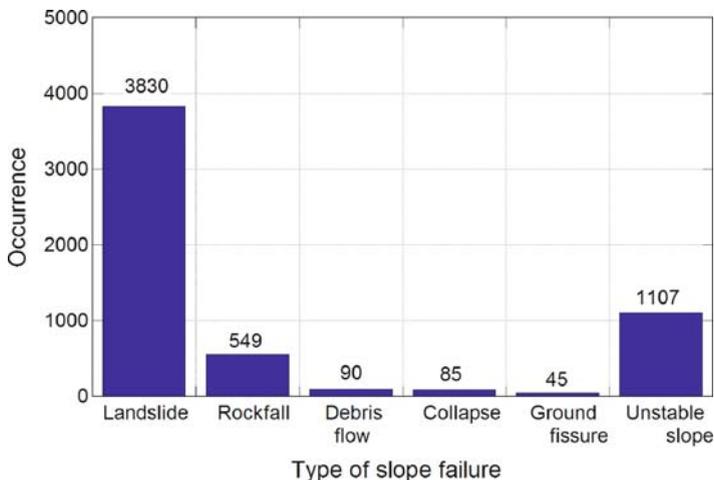


Fig. 1.2 Number distribution of geo-hazard types in the Three Gorges reservoir region

Calculation and Analysis of Assessment

The spatial database and layered graphics database using digital terrain is a 1:250,000 Base Map in MapGIS of Three Gorges reservoir area that is based on the data from 19 counties (districts) survey. Through statistics obtained by research of geological disasters and terrain (elevation, slope), water system, vegetation, rock groups of geologic engineering, active geological structures, slope type, rainfall distribution, seismic activity, evaluation of the regional development factor, basic factor, trigger factor, and vulnerability factor system of geological disasters in the Three

Gorges reservoir area were identified. A 2.5 km × 2.5 km (figure – 1 cm × 1 cm) grid throughout the region (a total of 9,309 grids), the numerical distribution of “distribution degree,” “potentiality degree,” “dangerous degree,” and “harmful degree” were calculated, and entered onto the corresponding zoning map using interpolation methods (Liu et al. 2004b).

1. *Distribution degree calculation:* According to the results of regional geological disasters “distribution degree,” and considering various hazard factors and the actual situation in the Three Gorges reservoir area, the development degree of geological disasters in the Three Gorges reservoir area is divided into four categories: the development of geological disasters indicating none (0–3), low growth (3–6), normal area (6–9), and high growth (≥ 9).

By viewing all levels of district size disaster distribution and percentage of geological disasters in the Three Gorges reservoir area, “distribution degree,” it can be ascertained that the development zones have their own different characteristics (Table 1.1).

2. *Potentiality degree calculation:* According to survey data and the actual results of geological disasters in the Three Gorges reservoir area, the basis factor and response factor of geological disasters are the discriminate factors of the “potentiality degree” calculation (Table 1.2).

Calculated by the composite index model, the “potentiality degree” curve jumps to 1.6, 2, 2.4, and 2.8, using the four points to divide the Three Gorges reservoir area into five geological disaster potential (degrees) districts: great (>2.6), rather high (2.3–2.6), high (2–2.3), low (1.6–2), and rather low (0–1.6) (Table 1.3).

“Potentiality degree” division results are inoculated with geological background, terrain, and other factors, and the division results can be considered as the disaster forecast foundation for the geological danger forecast for the Three Gorges reservoir area and additionally, geological disaster early warning.

3. *Dangerous degree calculation:* “Dangerous degree” must be calculated using composite index model, and in addition, using the basic factor and response factor, we also need to establish a trigger factor system (Table 1.4). “Dangerous degree” exponential curve calculated by the composite index model corresponds to the interval changes 2.2 and –2.4, 2.5–2.6, 2.8–3, and 3.4–3.5. The whole region will be divided into five risk areas indicated by the results of the analysis and the study of “potential degree” distribution: great (>3.5), rather high (3.2–3.5), high (2.8–3.2), low (2.4–2.8), and rather low (1.5–2.4) (Table 1.5).

Table 1.1 Geo-hazard “distribution degree” division

Distribution degree	None	Low	Normal	High
Hazard points	7	1599	1641	2459
Area(km ²)*	39425	9318.75	5456.25	3981.25
Points/km ²	0.00019	0.17160	0.30064	0.61769

*Grid unit includes the reservoir area outside the boundary of the grid area.

Table 1.2 Weighted basic and response factors of geo-hazard in the Three Gorges reservoir area

Discrimination factor		Discriminate parameter value*					Weight	
Basic level	High level	Unit	<250	250-400	400-600	600-1000	>1000	
Basic factor	Terrain	M	<250	250-400	400-600	600-1000	>1000	0.06
		Assign	5	4	3	2	1	
	Slope gradient	o	<10	10-25	25-40	40-60	>60	0.1
		Assign	4	5	3	2	1	
	Slope type	Code	I	II	III	IV	V	0.07
		Assign	2	3	4	5	1	
	Gulch density	km	0-2	2-3.5	3.5-5	5-6.5	>6.5	0.07
		Assign	1	2	3	4	5	
	Cover degree	%	<10	10-50	10-50	10-50	>50	0.04
		Assign	2	3	3	3	1	
Rock group	Type	Code	HM	HC	HD	SD	SQ	0.15
		Assign	2	3	4	5	1	
Geologic structure	Developed degree	Intensity	Intensity	Rather intensity	Normal	Rather feebleness	Feebleness	0.06
		Assign	5	4	3	2	1	
Disaster frequency ratio		Assign	0-1	1-2	2-4.5	4.5-8	>8	0.07
		Assign	1	2	3	4	5	
Disaster area modulus ratio		Assign	0-1	1-2	2-3	3-4	>4	0.04
		Assign	1	2	3	4	5	
Disaster area capacity modulus ratio		Assign	0-1	1-2	2-3	3-4	>4	0.04
		Assign	1	2	3	4	5	

*Discriminate parameter value is valid in the 2.5 km × 2.5 km calculating range.

Table 1.3 “Potentiality degree” division characteristics

Code	Name	PP	Area percentage(%)	Annotation
1	Level 1	0–1.6	9.56	Rather low
2	Level 2	1.6–2	29.71	Low
3	Level 3	2–2.3	29.70	Rather high
4	Level 4	2.3–2.6	24.41	High
5	Level 5	>2.6	6.62	Great

Table 1.4 Weighted induced factors of geo-hazard in the Three Gorges reservoir area

Trigger factor								
Rain capacity	1 day max	mm	<150	150–200	200–250	250–300	>300	
		Assign 1	1	2	3	4	5	0.05
	3days max	mm	<200	200–400	400–600	600–800	>800	
		Assign 1	1	2	3	4	5	0.08
	On average a year	mm	<1000	1000–1200	1200–1400	1400–1600	>1600	
		Assign 4	4	5	3	2	1	0.06
Earthquake intensity	Intensity		IV	V	VI	VII		
	Assign		2	3	4	5		0.03
Human activity			Great	High	Normal	Rather low	Low	
	Assign		5	4	3	2	1	0.08

Table 1.5 “Dangerous degree” division characteristics

Code	Name	DP	Area percentage(%)	Annotation
5	Level 5	>3.5	5	Great
4	Level 4	3.2–3.5	17	Rather high
3	Level 3	2.8–3.2	35	High
2	Level 2	2.4–2.8	28	Low
1	Level 1	1.5–2.4	15	Rather low

Table 1.6 Weighted vulnerability factors of geo-hazard in the Three Gorges reservoir area

Distinguishing factor									
Vulnerability factor	Basic level	High level	Unit/km ²	Discriminate parameter value			Weight		
				<100	100–200	200–400		400–650	>650
Vulnerability factor	Population density		Assign	1	2	3	4	5	0.4
	Property		Assign	–	–	–	–	–	0.3
	Engineering facility		Assign	–	–	–	–	–	0.3

Table 1.7 Geo-hazard “harmful degree” division

Harmful degree	HP	Area percentage(%)	Annotation
Level 1	0–0.5	15.94	Low
Level 2	0.5–0.8	34.01	Rather low
Level 3	0.8–1.2	33.62	High
Level 4	1.2–1.4	11.37	Rather high
Level 5	>1.4	5.06	Great

4. *Harmful degree calculation*: According to the actual situation in the study area, the selected vulnerability factors are population density, property value, and engineering facilities (Table 1.6). The deficiency of the information on property and engineering facilities resulted in only the evaluation of population density to be selected as the vulnerability factor. According to the changes in population density and disaster point distribution, the population density is divided into five sectors, and was assigned as, the population density of up to 5, and a minimum of 1. The actual calculations only took into consideration, population density multiplied by the 1/10 of the assignment from small to big according to discriminate population density and no weighted calculation, as shown in Table 1.7.

The study divided five “harmful degree” levels to consider the actual situation in the Three Gorges reservoir area. The calculation was evaluated as great (>1.4), rather high (1.2–1.4), high (0.8–1.2), low (0.5–0.8), and rather low (0–0.5).

Disaster Prevention Measures

According to the calculation and division of “distribution degree,” “potentiality degree,” “dangerous degree,” and “harmful degree” results, economic and social development planning, immigration relocation planning, and other factors affecting the Three Gorges reservoir area, different levels or different types of zones would be delineated. Level 3 “dangerous degree” and “harmful degree” in the area are for general prevention. Level 4 and level 5 “dangerous degree” in the area is focused on early warning, respectively, for 2708 km² and 9209 km². Level 4 and level 5 “harmful degree” areas have a major distribution, of 2741 km² and 6159 km².

Initiation Mechanism of Complex Slope in the Three Gorges

The initiation mechanism of complex slopes in the Three Gorges of the Yangtze River is not only a simple academic problem but also an emergency requirement for resettlement projects and reservoir banks protection, involving the basic problems such as the geological environmental quality and engineering construction capacity. It would be much more useful to expand our hazard assessments to be more inclusive of these factors, and not to simply continue to study landslide processes, only.

Facts and Viewpoints

Basic Facts

The attitude of the stratum in the Wanzhou area is gentle, but there are a large number of landslides. Resettlement and reconstruction are impacted by several landslides, such as the Taibaiyan landslide, Diaoyanping landslide, Pipaping landslide, Anlesi landslide, Caojiezi landslide, and Yuhuanguan landslide.

Landslide disasters are serious along the Yangtze River in Yunyang county, and there are many large bedrock landslides. The Baotaping landslide is one of the four landslides with volumes that are more than 1×10^9 m³ in the reservoir area, and the stability of its middle and back part is worth researching. The new location of Yunyang is away from the landslides group in the old city, but there are still landslides in Saiba, where the attitude of the stratum is gentle.

City construction of Fengjie county shows that the slope stability gradually decreases from west to east, and the landform is cut acutely. In the process of the new county city construction, large-area accumulation bodies with complex structures whose initiation is undefined are found. Because of the scarcity of geological evaluations addressing reasonable development, the new county city is 13 km long, and it has eight pieces of construction. There is no unambiguous geological assessment verdict in Baotaping and the old city extending to Sanmashan, road along the river, and junction road area, so as a result, new county locations have been changed several times.

Slope structure in Wushan is that of uncompaction. In the construction process of the new city resettlement, it was found that the geological foundation and the characteristics of roads, bridges, and building grounds are complex. The component, structure, initiation, and stability of slope rock mass and soil are key problems. Wushan is considered to be a typical spot of “down-slope overlapping.” Unusual clay with carbon is found, indicated by drilling, but there is rubble above and clay underneath. This phenomenon occurs in Fengjie, which shows that there was an absonant component during normal evolution.

The new location of Badong County town has been selected three different times and moved twice. The new location of Badong county city was first determined in Huangtupo in 1982, but it was found that there was a huge ancient landslide (Huangtupo landslide), during the investigation process in 1988, so the location had to be re-selected. Badong county city center was planned to be located in Yuntuo in 1992, but the location had to be moved once again because of the abnormal geological body. The government agency center of Badong county city was planned for Xirangpo, in the third location selection in 1996.

Scientific Knowledge

The resettlement locations of cities in Three Gorges reservoir area have been changed many times because the geological composition of the environment and the structure and failure initiation of geological bodies assessed by engineering

excavation are unclear. In addressing this problem, some scholars propose different conceptions, such as characterizing the geology as for instance, “compound accumulation body,” “down-slope overlapping,” “landslide,” “loose deposits,” “cataclastic rock mass,” “ancient collapse of underground river,” or “corrosion settlement body.” Due to the lack of systemic analysis and the limitations of individual viewpoints, these conceptions are unlikely to be unified descriptions, anytime soon.

For these viewpoints, down-slope overlapping, proposed by Cui Zhengquan, an engineer, has involved decades of observation. But there is a lack of evidence for ascribing this activity to global earthquakes, landslides, and floods of 200,000 years ago.

Liu CZ proposed the conception of “compound accumulation body” based on decades of site investigation and research in Three Gorges. It is the general name of a slope composed of bedrock, ancient collapse deposits, ancient collapse and landslides, and quaternary deposition. He ascribes the initiation to the abnormal reservoir bank rebuilding that occurred when the ancient Chuanjiang River was connected with the Xiajiang River at Qutang Gorge in Fengjie county, forming a unified Yangtze River (Liu 2000, 2005).

Regional Geological Evidence

Regional Geological Structure

There is geological evidence that the ancient Chuanjiang River was connected with the Xiajiang River at Qutang Gorge in Fengjie county to form a unified Yangtze River (Fig. 1.3). Three Gorges is mostly in the junction of the Chuandong fold belt, the Dabashan arc, and the west part of the Huaiyang Mountain shape reflex arc. Fengjie is the dividing point of regional sedimentary facies, in the west, which is mostly Jurassic red beds, and in the east, mostly Triassic carbonate rock (Chen 1993). In geomorphology evolution history, it is a karst collapse region in Fengjie, where a world-famous spectacle occurred, Tiankeng and Difeng. Before connection, the Caotang River which belongs to the Chuanjiang river system flowed west, while the Daxi River which belongs to the Xiajiang river system flowed east. These two rivers cut through the Qiyue Mountain anticline and the Qutang Gorge formed, and thus, the unified Yangtze River came into being (Fig. 1.3) (Tian 1996).

Neo-tectonic Stress Field in the Three Gorges Region Inversed Analyzed by River System

Formation and development of modern topography and geomorphology are controlled and affected directly by neo-tectonic movement. River systems are very sensitive to neo-tectonic movement, and its morphology has important significance in determining the neo-tectonic stress field. The method that calculates neo-tectonic stress fields, utilizing regional river system statistics, is more and more important (Koleback & Scheidegger 1977, Liu 1993a, Qin et al. 2006).

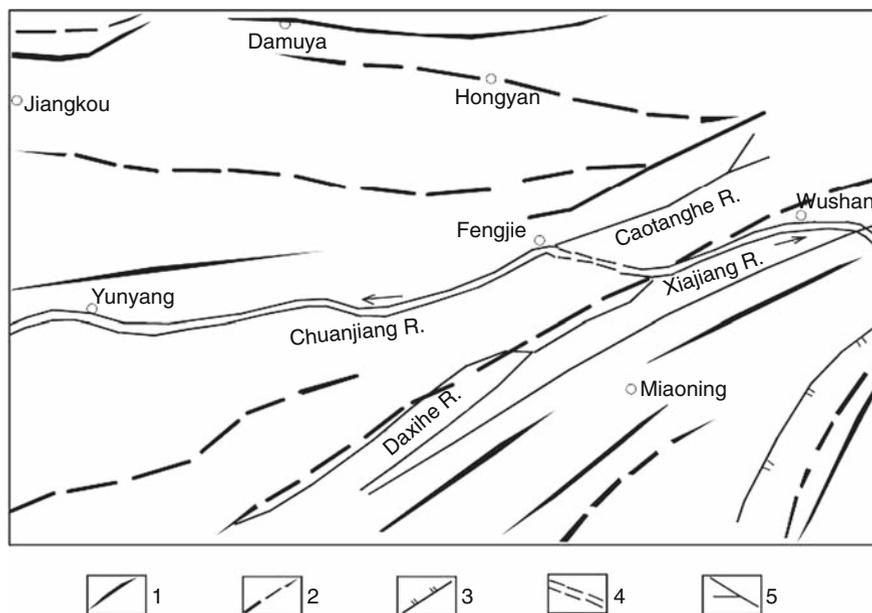


Fig. 1.3 Structural outline map in the connected area between Chuan and Xiajiang rivers. 1 – Anticline; 2 – syncline; 3 – faults; 4 – Qutang Gorge at present; 5 – water system (simplified from Tian 1996)

After arranging the river system data, the node coordinate of every river broken line can be obtained through the second development of MAPGIS software utilizing visual basics. Then a line is fit, the slope and arctangent of which is obtained through linear fitting using the least square method. River system-dominant trends can be calculated utilizing the azimuth of the fitting line and river length, obtained from the river file. It is then that the principal compressive stress can be obtained.

The dominant direction of the neo-tectonic stress field in the Three Gorges is the NE direction, and it is in a NW direction in A2 and B5. Stress field distribution shows the inherent neo-tectonic movement, which is the inherent activity of an old fault. The NE direction is dominant showing that NE is the direction of principal compressive stress. The neo-tectonic stress field in the Three Gorges appears to be in a NE direction, about 42° .

River System Fractal Character

According to fractal theory, based on GIS technology, utilizing the box-counting method with the digital topographic map, the fractal dimension of Three Gorges can be calculated (Mandelbrot 1982, Liu 1993b). Side length (km) $\varepsilon=165.40, 82.70, 41.35, 20.675, 10.34, 5.17, 2.58,$ and 1.29 . Box counts are 2, 8, 28, 94, 336, 1133, 3276, and 7846 respectively. The fractal dimension of the river system in Three Gorges is 1.7239, and the correlation coefficient is 0.9985063.

Generally, the fractal dimension of a river system reflects the development degree of the river system, and the difference of fractal dimension reflects the developmental difference in degree of watershed topography. According to the fractal dimension calculation applied to river systems of China, the critical fractal dimension of watershed topography development stage is $D = 1.6$, when $D < 1.6$ is reached, watershed topography is in a young stage. When $1.6 < D \leq 1.89$ is reached, watershed topography is in a mature stage. When $1.89 < D \leq 2.0$, watershed topography is in a mature stage (He & Zhao 1996).

The fractal dimension of the river system in the Three Gorges is $D=1.7239$, so watershed topography is in a mature stage and the river system development has been basically completed. With the Three Gorges Project finished, river system erosion will slow down, and it will be in a weak erosion stage.

Supergene Dynamic Phenomenon

A series of supergene dynamic phenomenon show that the Fengjie–Wushan area has been an abnormal region of crustal movement since the middle Pleistocene.

1. *Terrace characteristics:* The longitudinal profile of terraces shows that terraces in the Fengjie–Wushan area are abnormal. From Jiangjin to Fengjie–Wushan, all terraces are mostly parallel to a kraurotic water line and change gently. But the inclination of a downstream terrace in the east of Fengjie–Wushan increases suddenly. Terraces intersect the kraurotic water line with a sharp angle, forming a turning point in the Fengjie–Wushan area (Fig. 1.4) (Shen 1965).

2. *Riverbed characteristics:* The water level gradient is 0.16–0.17 from Jiangjin to Fengjie. It is even higher, as much as 0.4, from Fengjie to Wushan, which is the

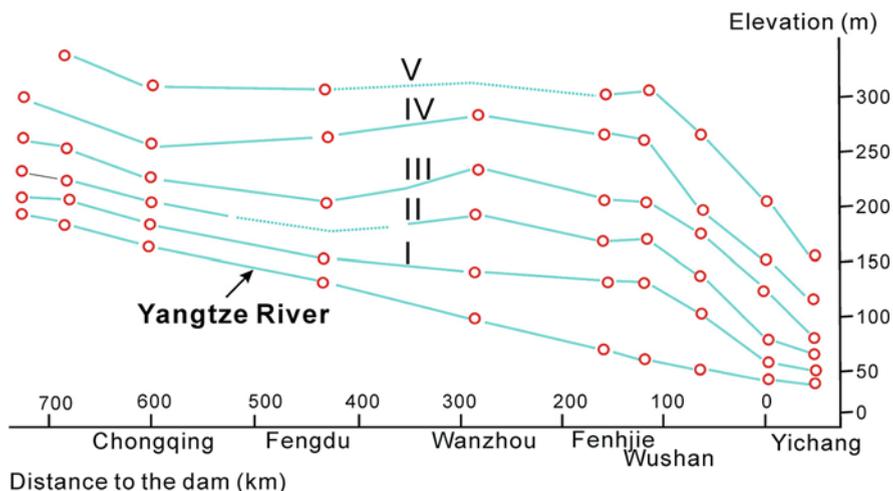


Fig. 1.4 River terrace altitude in the Three Gorges of Yangtze River

highest of the whole river. Tributaries of the Yangtze River also have greater riverbed gradient.

According to 1:12000 scale statistics in the Yangtze River channel, there are 141 shallow troughs, troughs, and deep troughs, 31 of which are lower than sea level and 30 are in Three Gorges. The lengths of shallow troughs, troughs, and deep troughs in Three Gorges account for 53.2% of the total length from Chongqing to Yichang, but the river length of the Three Gorges area is less than one third of the whole river (Table 1.8) (Yang 2006).

3. *Landslide activity*: Regarding elevation distribution, toe elevations of landslide are mainly between 60 and 200 m, and the back edge elevations are mainly between 60 and 200 m. The difference is generally 250–350 m, and the maximum is 730 m (Deng 2000). Dip angle of slip surface is generally 20°–40°. Ancient landslide dating in the junction region shows that nearly all the landslides happened in Q₂ or Q₃, coinciding with the warm and wet climate period (Zhang 1993). According to statistics, from Wanxian to Badong, landslides happened during 4 periods: (35–45) × 10⁴ a; (25–30) × 10⁴ a; (8–15) × 10⁴ a; and (2–5) × 10⁴ a (Fig. 1.5).

According to slip soil dating, the climax number of landslides happened in two periods: 40 × 10⁴ YBP (years before the present) and 7–15 × 10⁴ YBP. Landslides in Fengjie–Wushan took place mostly since the late Pleistocene, which shows that it was not a large-scale formation period before 15 × 10⁴ YBP in Fengjie–Wushan. Both sides of Fengjie–Wushan are in a violent formation period that is a landslide period. After 15 × 10⁴ YBP, Fengjie–Wushan entered a collapse and landslide period.

4. *Relationship between ancient collapse and landslides and the ancient Yangtze River*: Through geological investigation, deep erosion troughs were found on the toe of Baiyi'an ancient landslide and bedrock was not found at 18 m of elevation, which shows that the mainstream of the Yangtze River was closed to the Baiyi'an ancient landslide after a long period of landsliding (Liu et al. 2003). The stratum structure of the Baiyi'an ancient landslide also proves that the toe has always been

Table 1.8 Deep trough distribution in a section of Chongqing–Yichang section (Simplified from Yang 2006)

River section	Shallow trough*	Trough**	Deep trough***
Chongqing–Dahongjiang	1	5	0
Dahongjiang–Qingyanzi	5	0	0
Qingyanzi–Liushapo	0	14	0
Liushapo–Xinglongtan	9	0	0
Xionglongtan–Fengjie	3	13	1
Fengjie–Yichang	35	25	30
Total	53	57	31

*Shallow trough is 20 m lower than the river bed;

**Trough is 30 m lower than the river bed;

***Deep trough is lower than sea level.

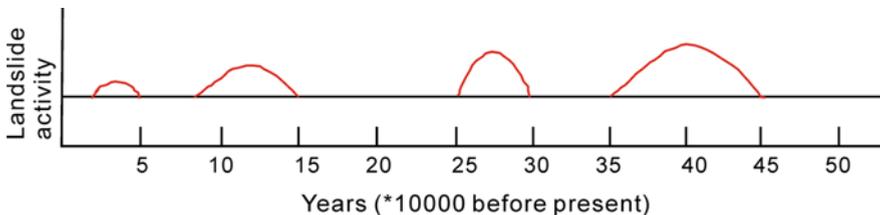


Fig. 1.5 Division of distribution periods for landslide activity

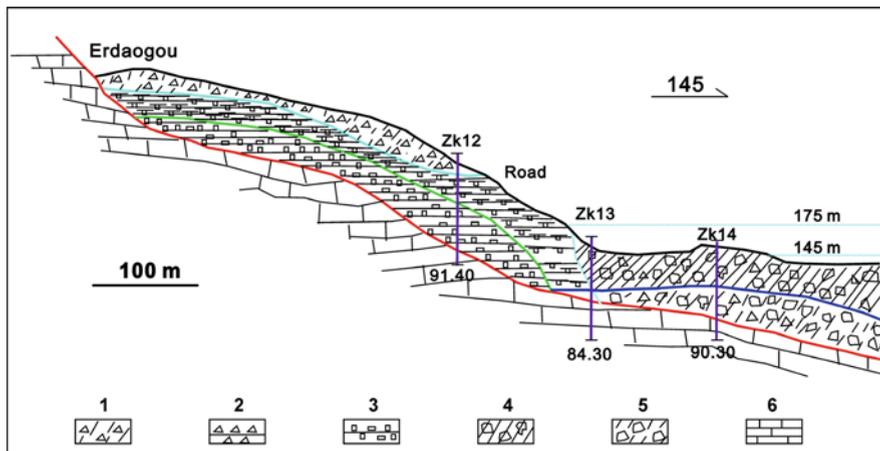


Fig. 1.6 Geological section of the Baiyi' ancient landslide at the northern bank of the Yangtze River. 1 – soil aggregate; 2 – fractured rock mass; 3 – fractured rock mass in block; 4 – silty clay with fractured rock piece; 5 – cobble soil with sand; 6 – Triassic marlite

the bank of the ancient Yangtze River. Subsequently, a cut slope formed and was covered by diluvium at a later time (Fig. 1.6).

5. *Collapse relic-Yanyudui*: “Yanyudui” was always a huge stone in the Qutangxia Gorge of the Yangtze River, which was 30 m long, 20 m wide, and 40 m high. It was blown up by 20 tons of dynamite to remove the barrier in the winter of 1958. “Yanyudui” was a typical collapse relic, which showed that huge landslides and collapses had always taken place in Qutangxia (Fig. 1.7).

Ancient Chuanjiang River Connected with Ancient Xiajiang River Forming a Unified Yangtze River and Slope Evolution

In this chapter, for the sake of convenience, the section of the Yangtze River from Yibin to Fengjie is called the Chuanjiang River and the section of the Yangtze River from Fengjie to Yichang is called the Xiajiang River. These two rivers belonged to a different river system in history, so the linking up and the evolution of these



Fig. 1.7 Rock fall trace in Qutangxia Gorge – “Yanyudui,” a huge stone (from Zhangzudao, photographed in 1956)

two rivers have important significance in engineering geology and environmental geology, which affect the quality of the geological environment, engineering construction capacity, and the ecological environment bearing capacity.

The Ancient Chuanjiang River and the Xiajiang River Linking up Was a Great Natural Event

Before linking up, the Chuanjiang River flowed west, while the Xiajiang River flowed east. These two rivers eroded headward in the direction of the Wushan–Qiyueshan area. After linking up, three dynamic water forces acted in a short time. These were, the “water saw” undercutting of Chuanjiang river on the top of the watershed, the headward erosion of the Xiajiang River, and an earthquake induced by underwater river collapse or karst collapse (Fig. 1.8).

These three processes caused a drastic reconstruction period and evolution process on the bank slopes of the river junction area. Under the action of “water saw,” slopes in the junction area changed, as a result of physio-chemical action. Structure fracture is the basis of bank slope shaping. The unloaded, loose, and cracked geological body with the space created by “water saw” turned muddy and collapsed, and eventually the final version of the collapse body come into being. Erosion of limestone and gypsum rocks caused the karst collapse or overhead collapse to occur on the top of the riverbed. Thus, the underground river turned into a surface-flowing

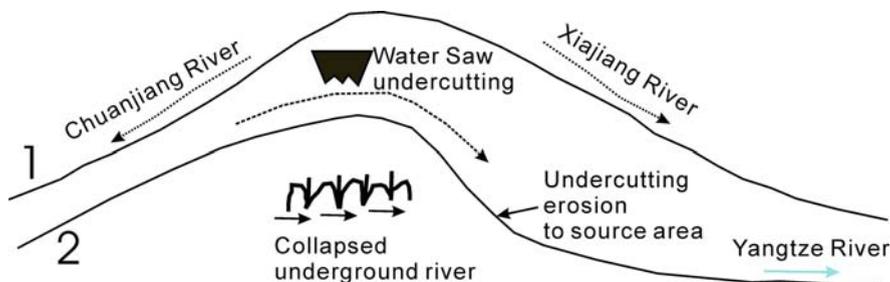


Fig. 1.8 The diagram of hydrodynamic action before and after the Chuanjiang River connected with the Xiajiang River in the Qutang Gorge segment of the Three Gorges at the Yangtze River. 1 – Geological processes before the Chuanjiang River connected with the Xiajiang River; 2 – geo-actions after the Chuanjiang River connected with the Xiajiang River, forming the Yangtze River

river. Surface collapse and landsliding contributed to the reformed process and overlapped with the alluvial–diluvial actions. The process of bank slope formation can be described as mountain unloading, characterized by loose, cracked, tumultuous mud-collapse and landslide-terrace formation overlapping with an accumulation of compound formations. The process is repetitive.

Basically, erosional action is obviously more pronounced in the junction area of the two rivers rather than in the adjacent area. The main area is the Yunyang–Fengjie–Wushan–Badong area. Fengjie–Wushan is the most intensive area and Wanzhou, Yunyang, Badong are the affected zones. The chronological progression of these processes is 60×10^4 YBP– 10×10^4 YBP, and they have evolved naturally since 10×10^4 YBP.

Geological Dynamic Background

In regard to regional geodynamics, China is located at the junction of the circum-Pacific tectonic region and Himalayan tectonic region. Subduction of the Pacific plate and extrusion activity of the Indian Oceanic plate in relation to the Pacific plate are the main geodynamic sources for mainland China. The Himalayan Mountains which are the highest mountains in the world, formed at the edge of the Indian Oceanic plate and Asian plate. A large ridge formation occurred, which is the Qinghai–Tibet Plateau. Convergence of these two active tectonic regions creates the tectonic framework and basic topographical configuration of China, which determines the diversity of geological environments and the frequency of geological disasters.

Research has proven that the Qinghai–Tibet Plateau has risen up quite a bit since the recent tectonic period and the west part of Sichuan became the second-level terrain step of China, which is the background for the Chuanjiang River connecting with the Xiajiang River. At the border of Sichuan province, Yunnan province and Tibet, the Nujiang River, the Lancangjiang River, and the Jinshajiang River flow parallel to one another. The Jinshajiang River changes a lot in Shigu town, and

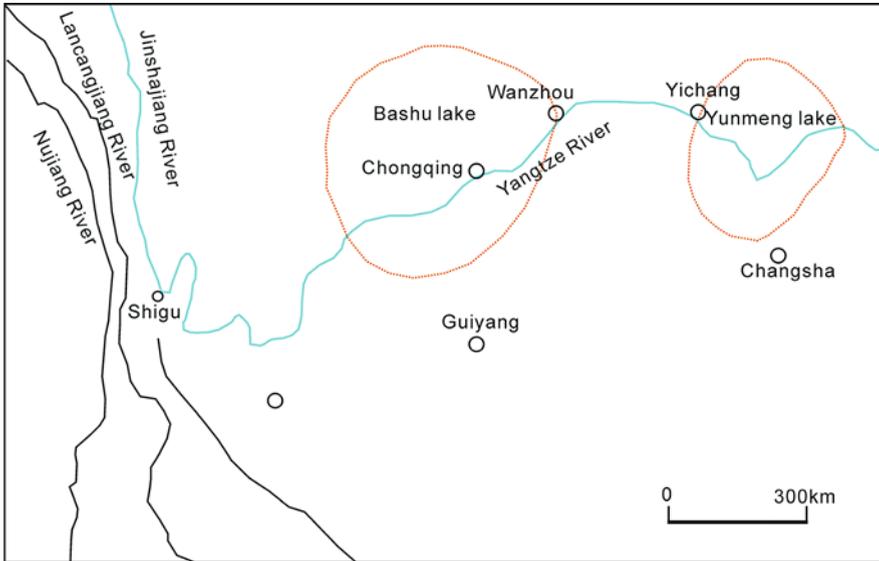


Fig. 1.9 Three rivers (Jinshajiang, Lanchangjiang, and Nujiang) flow in the same direction and converge to form the Yangtze River

Honghe River in the south of Shigu along the Ailao Mountains and is perhaps the relic of the Jinshajiang River flowing south. At the border of Sichuan province and Hubei province, the Xiajiang River belongs to a different river system; the west part belongs to Bashu ancient lake, while the eastern part belongs to Yunmeng ancient lake. Three Gorges allows the Xiajiang River to connect with Chuanjiang River (Fig. 1.9) (Liu 2000, 2005, Tian 1996, Shen 1965, Yang 2006, Lee 1924, Yang 1988).

The Complex Slope Failure Initiation and Assessment in Badong County

Statement of Problem

The initiation process of large complex slopes in the Three Gorges reservoir still does not have an acceptable evaluation, and the academic community also has not integrated knowledge of the characteristics of the fan-shaped slope at Badong new town in the Three Gorges reservoir, even if a few have researched micro-phenomenon survey to compare it with the “big question” from macroscopic-type research. This kind of “question” is the main reason for the new site selection and the numerous changes in location of Badong new town, and it is a typical instance

of new town planning that lacks the necessary research on regional engineering geology (Cui 1998, Liu et al. 2006a).

Throughout the course of about 20 years' planning and changes, Badong new town site has become five subzones, those of Huangtupo, Daping, Baitupo, Yuntuo, and Xiranpo, extending from the east to the west. Within the narrow, long area that is about 8 km in length and 1 km wide along the Yangtze River, the Badong big slope is divided into five slope units, delineated by four gullies (Aleotti & Chowdhury 1999, Haruyama & Kitamura 1984).

Reviewing history, the geological work during the course of planning and construction of Badong new town generally was dealt with passively, and the geological work was the guiding and leading evaluation approach for hazard studies and had not completely accounted for a through scientific investigation.

This one-sided approach did not adequately explain the complexities involved in assessing the hazard from landslides. The question about deep layers in the entire slide area of Badong big slope was put forward in 2002, and even then there were worries about whether there would be a calamitous hidden danger such as that which occurred at Vajont reservoir in Italy.

This research tries to address the mistaken aspects of the overall conclusion that is drawn from local phenomenon. Based on the analysis of morphological features and geological structures, the complex slope system of Badong was found to be the example for failure initiation and for the assessment of geologic environmental quality and dynamics.

Geological Characteristic of Badong Big Slope

Morphologic Features

- (1) The morphologic features of the Badong big slope belong to the characteristic middle-low gorge area with areas of structural erosion. The mountain top elevation is 700–1230 m, and the elevation of the river before impoundment of the Three Gorges reservoir is 67.1 m. The Yangtze River flows across the edge of the Badong big slope becoming a northward arc, and the width of the river surface is 300–600 m, which is the relatively widest reach of the Three Gorges.
- (2) The Badong big slope is a fan-shaped slope where the strike is nearly east–west and the incline is north. There are a series of deep and big gullies in the slope area, and the gullies pass through the slope from south to north and enter into the Yangtze River. The whole area was cut into five slope units, forming widths of from 1.3 to 1.7 km, the distribution being nearly south–north (Fig. 1.10).
- (3) The gullies in the slope area are short and deep cut, merging into a single gully, and many gullies have the same source. They reflect the numerous occurrences of landslide development under the control of the geological structure.
- (4) The cross section of gully generally is a “V” type, the depth cut is 50–200 m, and the greatest depth is 350 m (Baiyangou). The cut depths of Tongpenxi and Huangjiagou are 20–150 m, they have many falls, and the catchment areas are both greater than 2 km². The lengths are both greater than 2 km.



Fig. 1.10 Aerial map of the Badong large slope (from China Aero Geophysical Survey & Remote Sensing Center for Land and Resources (AGRS), 2003.4)

- (5) Terraces on the Yangtze River have rarely been found, indicating that the continuous downward erosion and the side directional hillside soil losses are large, occurring since the more recent period, and the phenomena of erosion gyration or landform erosion gyration are not found.
- (6) There are many remnants of riverbed at Badong on the Yangtze River and they are lower than sea level – some places are even up to 11.8 m lower. They are lower than the erosion base-level generally, and this indicates that there are deep pools which resulted from vortex erosion.
- (7) The trailing edge border of the big slope is an arc gully which resulted from the differential erosion of the contact zone of soft rock and hard rock. It became the back border of the whole slope and the source of all gullies, and it controls the gully situation within the slope.
- (8) There are five water systems within the slope, from the west to the east known as, Huangjiadagou, Tongpenxi, Baiyangou, Sidaogou, and Toudaogou, and their fractal values are 1.051, 1.111, 1.124, 1.012, and 1.114. The water system fractal value of the whole fan-shaped area of Badong is 1.267. All the fractal values are less than 1.6, and it indicates that the river basin belongs to the young period of erosional development; the water systems do not develop sufficiently (He & Zhao 1996, Lian et al. 2006).

Stratum Combination

The Badong big slope is made up of four lithologies of the Badong group (T_2b) of the Triassic Period middle system; it is an interlayered combination of clastic rock and carbonate rock. The fourth section (T_2b^4) is red sand-mudstone, and it is mainly distributed in Hongshibao and at the exit of Huangjiagou, and is the remnant of

karyomere of the Guangdukou syncline. The third section (T_2b^3) is carbonate rock and is the main body of Badong big slope. It is generally a rock mass with moderate weathering, some parts are intensely weathered, and they present a fractured rock mass with fissure development. The second section (T_2b^2) is fuchsia mudstone and silt-mudstone, they are mainly distributed at an elevation of 430–460 m, the rock is easily weathered, and subject to softening and argillization, and it is one of the most slide-prone strata in the Three Gorges. The first section (T_2b^1) is gray matter mudstone interlayer with micrite and dolostone, with banding distributed on the trailing edge of the Badong big slope, and they have become the sources of gullies in the upper reaches or the border valleys of the whole slope. The third section Jialingjiang group (T_{1j}^3) of Triassic Period lower system is medium thickness seam dolomite–limestone and limestone, interlayered with angular gravel limestone. It makes up the base of the Badong big slope, exposed behind the mountain, becoming the first watershed.

The Quaternary-age material is made up of residual slope deposits – demise diluvial (Q^{el+dl}) and demise deposits ($Q^{col+del}$), and some parts develop alluvium–proluvium, manual deposits (Q^{ml}), and debris flow deposits (Q^{sef}).

The Vestige of Geological Structure

The regional geological structure of the Badong big slope is generally simple, in that it is the south wing of the Guangdukou syncline made up of a monoclinical mountain, and some small-scale relaxed folds or fold distortion with strong extrusion formed by the geological reconstruction in some parts of slope. The loosening relief fracture, kinky deformation of soft rock, and collapsed landslides are very developed. The syncline is broad and relaxed, and the axial plane is slightly inclined to the south. The dip angle of the north wing is 10° – 25° , and the dip angle of the south wing is 20° – 48° . The structural axis of the Guangdukou–Donggrangkou syncline occurs near the river at new town, at the river entrance of Baiyangou and Tongpenxi. The geological structure of the fan-shaped big slope of Badong new town is a monoclinical slope which is made up of the south wing of the syncline (Fig. 1.11) (Geological Bureau of Hubei Province 1997, Yangtze River Conservancy of Water Resource Committee 1997).

The Question About the “Badong Fracture”

1. *The geological facts:* The trailing edge of the Badong big slope is nearly developed along the strata division of the Jialingjiang group (T_{1j}^3) and the Badong group (T_2b^1). It trends as an arc negative in relief, the middle area of the Zhongyuan village as watershed, and the east and west side develop along the upper reaches of Huangjiadagou, Tongpenxi, Sidaogou, and Toudaogou, and it is also the source of the branch gully of Baiyangou. Along the trailing edge valley, there are some typical sites with extrusion vestiges.

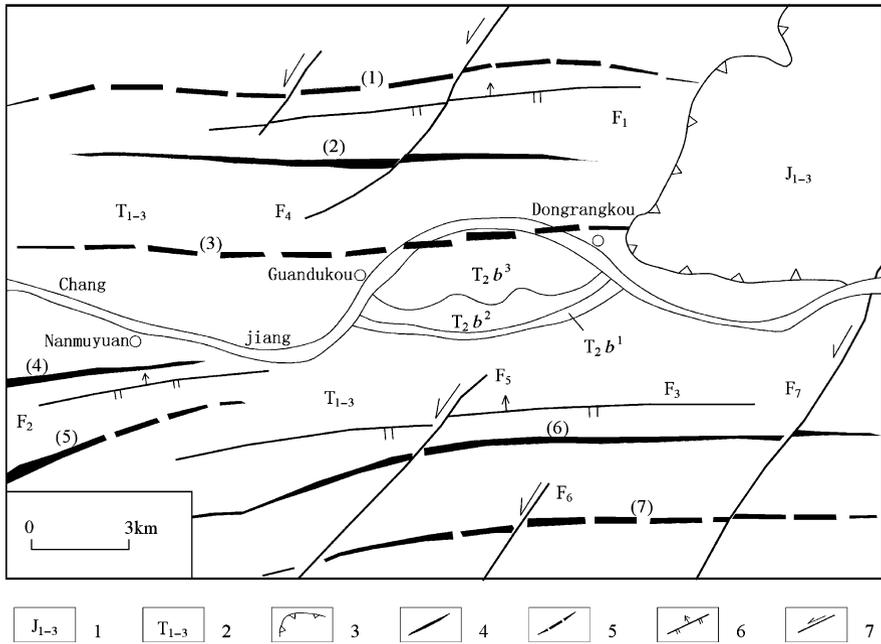


Fig. 1.11 Areal structure sketch of Badong slope in the Three Gorges of the Yangtze River. 1 – Jurassic System; 2 – Triassic System; 3 – continental deposit (Zigui) basin; 4 – anticline structure axis; 5 – syncline structure axis; 6 – reversed fault; 7 – shift fault. (1) – Huofeng syncline; (2) – Xiaogaoshan anticline; (3) – Guangdukou syncline; (4) – Nanmuyuan anticline; (5) – Duping syncline; (6) – Baifuping anticline; (7) – Fengcuiya syncline; F₁ – Guangyintang fault; F₂ – Bingshuijing fault; F₃ – Maluchi fault; F₄ – : Gongqiao fault; F₅ – Yeluchi fault; F₆ – Meiziya fault; F₇ – Niukou fault

- a. The extrusion breccias were developed at the corner of Mutianwan at the 209 national road, the color is lark, the shale content is high, and the angular gravel sizes are different. The small size is 3–5 cm, and the big size is 10–15 cm, the edge angle of angular gravel is not clear, the angular gravel is round, and slickensides can be seen. The weathering relief of the surface layer is pronounced and was shown as argillization. The strike of the extrusion is 105°, the incline is north, and the dip angle is 61°. The hanging wall is argillaceous limestone of T₂b¹, and the footwall is interlayered and is composed of thick and thin limestone of T₁j³.

The highway slope to the north about 100 m on 209 national road is made up of a fuchsia mudstone sliver of T₂b², Kelly gray matter mudstone sliver and deep gray limestone block, without bedding and separation. The geological composition is collapse deposits.

- b. The original breccia was found at the Jigongling (elevation 450 m) along the eastward end of the trailing edge border of Badong slope, and the breccia is crushed, loose, and unsupported. Its matrix is made from gray sand-

mudstone, argillaceous limestone, and limestone with non-rounded gravel. It is in the contact zone of the T_{1j}^3 and T_2b^1 stratum.

- c. Toward the east, at the place where the Toudaogou passes through the trailing edge border of Badong slope (elevation 290 m), the limestone angular gravel and the tan marl are intermixed, and the angular gravel has some rounding. The diameter of the gravel is 5–10 cm, and it has been cemented into rock, but the soft rock gravel has been corroded into the porous areas

2. *Basic acquaintance*

- a. The plane of the trailing edge border of Badong big slope is the result of tensile stress, and the trailing edge is expressed as transpression at the cross section. The Mutianwan extrusion is the local phenomena of transpression first and tension later. It is the result of a static landslide under gravity.
- b. The breccia is corrosion-collapse breccia, and it was cemented into rock by the deposits resulting from collapse and landsliding. It is not the structure breccia, and the fracture phenomenon does not exist.
- c. The width of the fractured zone of Mutianwan is 130–140 m, and it is composed of the deposits of collapse and landslides, as a fractured zone.
- d. According to the ESR, the value is 30×10^4 a; it is consistent with the valley evolution of the Yangtze River and corresponds to the middle and late period of the middle Pleistocene (Liu et al 2006a).
- e. There is creep indicated along the strata border of T_{1j}^3 and T_2b^1 of the whole slope.
- f. “Badong fracture” does not pass through the river at both sides of the east and west, and it is only shown as a fold phenomenon.

Therefore, it is mistaken to take the local extrusion, corrosion-collapse breccias, and deposits of collapse and landsliding of the trailing edge border of Badong slope as facture structures.

Joint and “Fracture” of Slope Area

According to the data, the whole Badong slope has 62 data points referring to fractured zone width (Yangtze River Conservancy of Water Resource Committee 1997, Hubei Hydrogeology and Engineering Geology Team 2001). It is interesting to note that the site, structure, property, and width of the fractured zone were recorded in detail by predecessors, but the length was rarely mentioned. We can find that the width is less than 1 m accounting for 41.9% of the 62 data points, 1–5 m account for 32.3%, 5–10 m account for 11.3%, and greater than 10 m account for 14.5%.

Generally speaking, the width of the fault corresponds to its length, and it cannot be just the local geological behavior that the fractured zone reaches a certain width. It is through the local gravity function that the fractured zone width can be seen at cross section, as it rarely can be seen at the ground. Many “faults” of the Badong slope area described by predecessors were the vestiges of relief, extrusion

deformation, and collapse landslide; they are not the inner-dynamic structural cause of failure.

Geomechanics Model of Superficial Deformation and Damage

The superficial geological vestige of Badong slope can be summed up by six geo-mechanics damage models, reflecting the mountains with dip slope geological structure, quickly becoming a free face and thus, gravity lateral relief and collapse-landslide processes came into being under the action of quick corrosion and cutting by the flow of the Yangtze River.

1. *Lateral drawing crack model*: The main initiation of slope failure is human activity, such as excavation of building foundations or highway cut-slopes, and these may result in failure scarps occurring in a short time. This may result in mountain relief along the lateral direction. The rock mass may fall away along the fracture, and the block may slip or even form into a landslide (Fig. 1.12).

2. *“Avalanche type” collapse model*: The deformation type at the leading edge of the Badong slope can be found at every strata layer, but the contact zones of T_{1j}^3 and T_2b^1 and the rock mass distribution of T_2b^3 are typical, and they are generally shown as corrosion-collapse breccia deposits (Fig. 1.13).

3. *Surface layer weathering model*: Distributing near the river at the trailing edge of the Badong big slope, they are shown as an imbricate type at the geological cross section, and then developed into a small-scale rock fall phenomenon (Fig. 1.14).

4. *Lateral slip translation rupture model*: Mainly appears in the brittle rock mass distribution of T_2b^2 and T_2b^3 . The translation fissures are dense in rows, and shown as a certain equidistance, and formed into fractured zone at the macrocosm (Fig. 1.15). This slope model is transformed, once sudden collapse occurs, and the avalanche-type destruction form will occur and become what is called a “fall and cover mass” (Cui 1998).

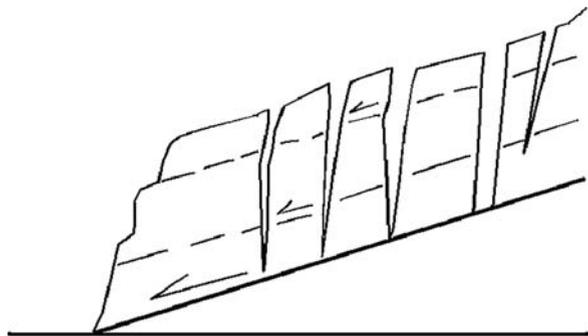


Fig. 1.12 Lateral drawing back failure

Fig. 1.13 “Avalanche type” collapse model

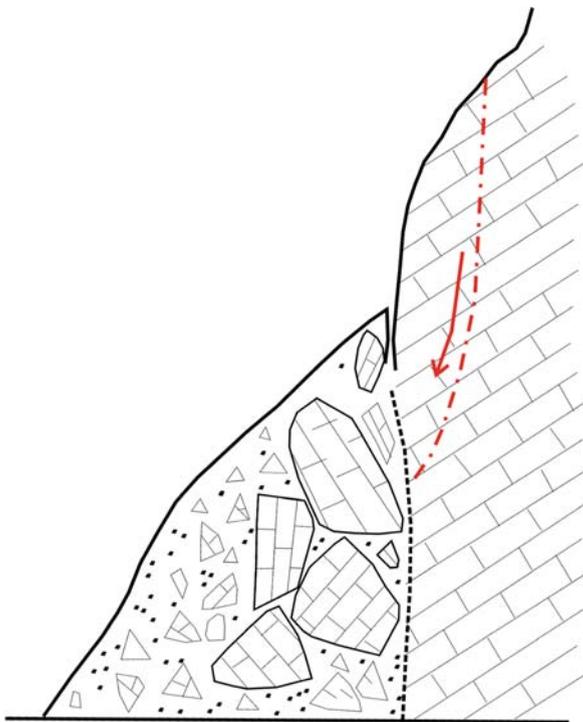


Fig. 1.14 Surface layer weathering model

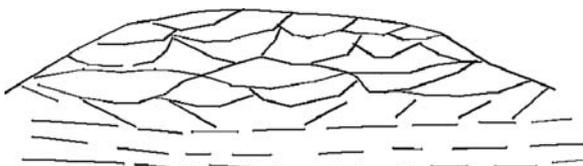


Fig. 1.15 Lateral slip translation rupture model

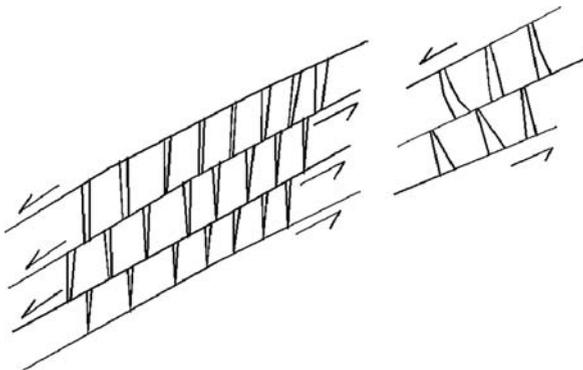


Fig. 1.16 Rock stratum breaking and shift model

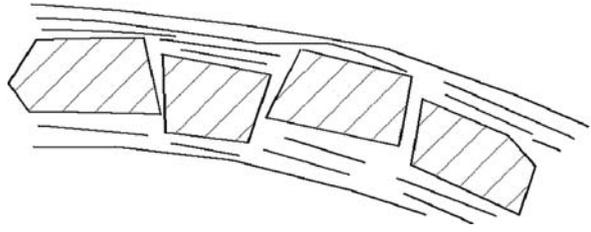
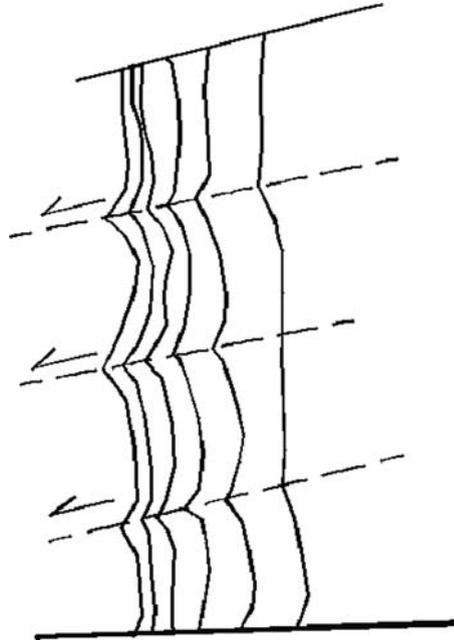


Fig. 1.17 Soft rock kink shear rupture model



5. *Rock stratum breaking and shift model*: Mainly appears in the T_2b^3 marl interlayer occurring as a soft rock sandwich, interlaid with hard rock. This process also appears in the T_2b^2 marl interlayer distribution (Fig. 1.16).

6. *Soft rock kink-like shear rupture model*: Mainly appears in the T_2b^3 marl with thin-bed distribution. The interlayer slip cuts off the dense tension joint and appears as a kink effect (Fig. 1.17).

Badong Complex Slope System and Its Failure Initiation

Badong Complex Slope System

Based on the monoclinical mountain at the south wing of the Guandukou syncline, and given the strongly cutting erosion of the great geological incident of the Yangtze River run-through as the dynamic force, the complex slope system of Badong was

gradually formed by the process of local folding, layering slip, breaks with layers, many gullies with the same source, and a collapse-landslide formation, formed in stages and zones. Geological structure, initiation type, and space distribution in the Badong slope system can be divided into three layers, namely the deposit layer of surface layer collapse landslide, the middle bedrock layer with gullies and superficial geological vestige development, and a deep partial bedrock layer of a continuous and straightforward incline.

The surface layer is made up of the deposits of the landslide that happened in different areas and time, or human activity. Its Quaternary period deposits are relatively isolated and are easily subject to geological hazards. The middle bedrocks are made up of the T_2b^2 , T_2b^3 , and T_2b^4 bedrock mass that was cut by the Yangtze River and gullies, the layers are relatively integrated, but show a discontinuous characteristic due to the cutting by gullies. The layers generally are straightforward in inclination, and the geological vestige of local fold, layering slip, and fractures within layers are developed; it is the key layer for maintaining the superficial geological vestige. The deep part bedrocks under the middle bedrocks and above the T_{1j}^3 generally are a straightforward incline, and they mainly consist of T_2b^1 , T_2b^2 , and T_2b^3 that are not cut by gullies – the whole structures are continuous and integrated, and do not have the failure condition.

Taking the Tianxiangling–Zhaoshuling slope unit as an example, the western part of this slope unit is Huangjiawuchang, the landform where the elevation is between 200 and 275 m and is integrated and gentle, the slope angle is 5° – 15° , and above 275 m, the slope angle is 15° – 25° . The eastern part of the slope system is the famous Zhaoshuling ancient landslide. The landslide surface has three platforms, and their elevations are 150–200 m, 350–425 m, and 450–525 m. The top of the slope is Tianxiangling, and the elevation is 700–800 m, and the visible strata are T_2b^3 and T_2b^2 of the Badong group. The trailing edge of the slope passes through the Badong arc gully of which the lithology is T_2b^1 of the first section of Badong group. It is the highest mountain in the area with an elevation exceeding 800 m, and the lithology is T_{1j}^3 of the Jialingjiang group.

The material of the Zhaoshuling landslide mainly comes from T_2b^3 , and some come from T_2b^2 . There are mainly three kinds of landslide materials, namely, sliding rock mass, stone fragments with soil, and soil aggregate. The sliding rock mass mainly distributes at the elevation of 100–400 m. The rock mass shows bedded structure and keeps to a certain sequence. The thickness of the sliding mass is 34.6 m (Yun-13 hole) – 99.09 m (Yun-11 hole); the anterior part of the sliding mass overlaps the normal bedrock and appears at the boundary of T_2b^{3-1} and T_2b^2 repeatedly, in the vertical direction. Between the Yun-5 hole and Yun-21 hole, the sliding rock mass shows an anticlinal shape, and the geological characteristics around the edge of the sliding mass indicates that this original anticline is part of a large, dissolved cavern anticline, and the mass then slid to its current location. It can be inferred that the horizontal sliding distance is about 500 m. The sliding masses at the south of Yun-14 hole are mostly fragmented stone with soil (Fig. 1.18).

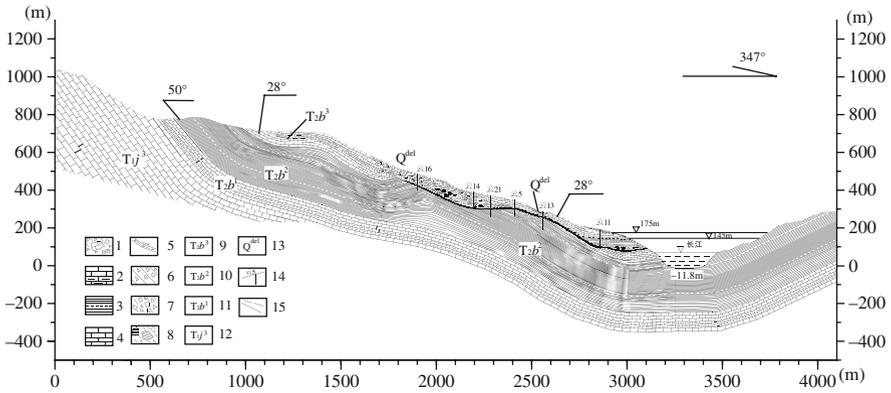


Fig. 1.18 Geological profile of Tianxiangling–Zhaoshuling. 1 – Gray limestone, fragmented stone with soil; 2 – limestone, marl; 3 – mudstone, siltstone, mud-siltstone; 4 – limestone; 5 – slip band; 6 – fragmented stone; 7 – fragmented stone with soil; 8 – red mudstone, fragmented stone with soil; 9 – the third section of Badong group; 10 – the second section of Badong group; 11 – the first section of Badong group; 12 – the third section of Jialingjiang group; 13 – landslide deposit; 14 – borehole; 15 – the boundary of strata and lithology

The strong corrosion and cutting actions resulted in the bed elevation of the trailing edge of the Zhaoshuling landslide to be -11.8 m, but the elevations of the shearing outlet of the landslide leading edge are all above 65 m. The elevation of the landslide trailing edge is below 600 m, and these correspond with the elevations of the leading edge and the trailing edge of the whole Three Gorges. The profile structures reflect that the main shear strata of the landslide are layered slip, and that the tangent sheaf is minor.

Initiation Theory of Gravity

(1) Basic condition

- a. A wing of the Guandukou syncline formed the monocline mountain, and it has the structure of an inclining slide.
- b. The engineering petro-fabric which makes up the monocline mountain is clastic rock of continental deposit alternating as soft and hard, having the biological clastic rock of shallow marine facies. They easily facilitate bedding slip and even a bend failure at the terrain condition with free space. Not sure what “free space” means.

(2) The geological structure of the slope

- a. The arc boundary of the Badong slope trailing edge shows differential weathering, or a valley (deep gully) formed by wash, cementation of

corrosion-collapse breccia, deposits of loosening collapse landslide, and pressure-twisting slip of interlayered gravity relief.

- b. There are small-scale folds, ruptures, and joints inside the Badong slope, and their extensive development caused the geo-mechanics failure phenomenon of superficial gravity relief, such as mountain loosening deformation.
- c. Collapse-landslide incidence of different periods is generally developed at the elevation between 65 and 600 m, and they correspond with bank slope landslide distribution of the Three Gorges mainstream of the Yangtze River.

(3) Regional outside dynamic force

The ancient Chuanjiang River and ancient Xiajiang River linking up into Yangtze River caused the water to flow to the east. The flow increased severely and resulted in a special period of supernormal wash, erosion, and cutting. This outside dynamic force shaped the bank slope quickly, a steep free space formed and collapsed, landslide or underground water collapse happened severely, and it resulted in a local, unusual geological incident against the background of regional intermittent ascension.

The basic condition, inherent reason, and outside unusual dynamic force action described above form the collection of evidence for the gravity failure initiation theory of the Badong complex slope.

The three levels of division actually provide a regulation of the slope development in sequence with the Yangtze River's deep cutting and river valley widening. The deep level can be developed into the middle level, and the middle level can be developed into the superficial level. This is a geological course mainly based on gravitational action that happened with many instances of loosening, relief, and movement initiated with each other, due to the wash action by supernormal hydrodynamic forces and the formation of a steep, free-space slope.

The Badong complex slope system is made up of three levels comprising the geological body. Each slope unit and even each landslide area can be divided into lower sliding sequences. The Zhaoshuling landslide and the Huangtupo landslide can be divided into sliding blocks and slides of different scales and different period (Shen 1965).

Numerical Simulation Analysis with FLAC^{3D}

According to the numerical simulation analysis with FLAC^{3D}, we found the following results (Liu et al. 2007).

- (1) With the special stratum lithology and geo-structure of Badong slope, gravity action could make the slope slide along the interface between T_2b^1 and T_{1j}^3 (Fig. 1.19).
- (2) There was no mechanical condition in the trailing edge of the Badong slope, so it could creep minimally and no deep sliding of the whole occurred.

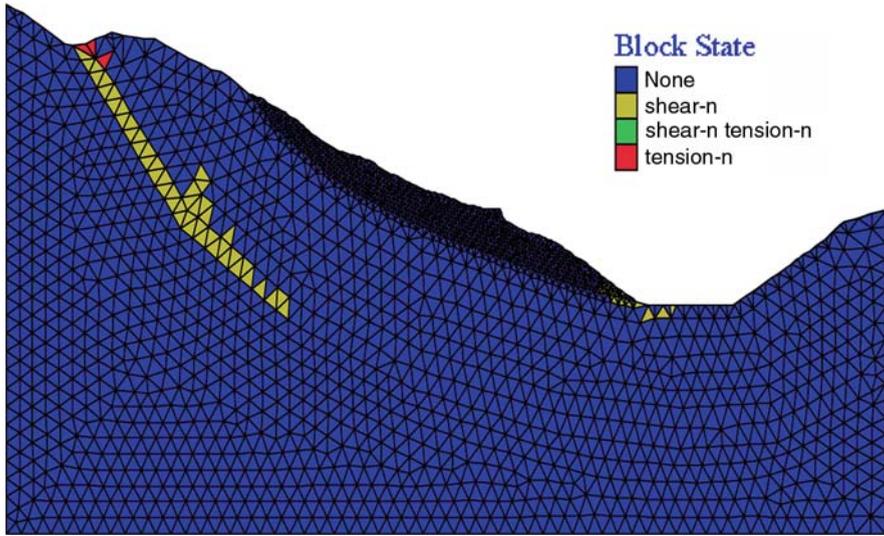


Fig. 1.19 Plastic zone distribution of the slope trailing edge

Regional Geo-environment Quality Assessment of the Badong Slope

Basic Idea

According to the application of geo-environmental sustainably and achievement of geo-hazard risk management, we should not limit our ideas to stability studies but should also research geo-environmental assessments to meet the requirements for an engineering construction program scale (1:10,000–1:50,000). To provide direction for carrying out the different types of regional geo-environmental assessment and to answer geological safety problems at the macrocosm scale, we gave the basic frame of regional geo-environmental assessment (Liu et al. 2006b).

Regional geo-environmental quality assessment, which is the acceptable degree of geo-environment in relation to people's activities, is the mutual goal. It is the primary objective of geo-environment for engineering.

Regional geo-environmental function division, which needs regional socio-economic development status and trend, is a functional division for the base components of geo-environmental quality assessments. With it, relevant engineering function division ideas and implementation can be obtained, for example, such activities as town building, basic infrastructure building and maintenance, rural community preservation, traffic control, and agricultural concerns such as woods, fruit trees, and vegetables. Regional geo-environmental capacity evaluation, which is based on relevant engineering types, scale, construction process, and operating characteristic, integrates the relationship between geo-environmental

and engineering construction. In different function zones, engineering construction capacity can be evaluated and its engineering bearing ability can be brought out.

Geo-hazard prevention risk management studies can evaluate geo-hazard risk probability and acceptability in the different function zones. Then, suggestions for alleviating geo-hazards can be formed. The theory base of risk management study is that geo-hazards such as landslide, debris flow, etc. behave as uncertainties but its uncertainty can be measured.

In practice, according to special engineering types in geo-environment function zone, engineering capacity evaluation and geo-hazard risk division should be carried out. Then, geo-hazard risk management suggestions can be given, which will be helpful to engineering safety.

Geo-environment Evaluation of Badong Slope

Twelve factors, such as altitude, gradient, gully density, slope type, engineering geological stratum sets, bedrock depth, etc., and their weight were used to evaluate the geo-environmental quality index of Badong slope. The method is an aggregate index model, shown in Table 1.9.

To find the threshold value of the geo-environmental quality index for its grades, typical zones were selected to check, and the following results were obtained: there were more landslides in two units, which had quality indexes that ranged from 2.4 to 3.0 and greater than 3.0. So, using this quality index, geo-environmental quality evaluation and division could be achieved (Liu et al. 2006).

The whole Badong slope area is 17.8832 km². In view of research and application, the Badong slope was divided into five grade quality zones. According to quality index distribution, quality index units could be merged and smoothed with MapGIS, then Badong slope quality evaluations were calculated (Table 1.10).

Geo-environmental function division, which was a new project, is the primary method advanced in the chapter. According to the geo-environmental quality division, the Badong slope was divided into, primarily, three grades of geo-environment function zones (Fig. 1.20).

Zone A, about 6.3728 km², 35.64% of the whole zone, includes grade-1 and grade-2 quality zones. Its geo-environmental capacity was the largest. The rock mass in zone A was stable, with bedrock exposed or buried in a shallow manner. Zone A could be extrapolated to include the town, where higher or multistory buildings could be constructed.

Zone B, about 6.0560 km², 33.86% of the whole zone, was a grade-3 quality zone. Its geo-environment capacity was in the middle, or medium. The rock mass in zone B was relatively stable, distributed in the slope's trailing edge, inconvenient for traffic but in a better natural condition, where forests or rural communities could be constructed. This zone could also be used for a wharf or port on the river bank.

Zone C, about 5.4544 km², 30.50% of the whole zone, included grade-4 and grade-5 quality zones. Zone C incorporated the main distribution of landslides,

Table 1.9 Value and weight of engineering geo-environmental quality evaluation factors

No.	Factor and unit		Class and value	Weight
	Factor	Unit		
1	Altitude	m	<200 200-350 350-500 500-700 >700	5 2 2 3 4
2	Gradient	Value °	<10 10-15 15-25 25-35 >35	1 2 3 4 5
3	Gully density	Value mm/cm ²	<1.6 1.6-3.2 3.2-4.8 4.8-6.4 >6.4	1 2 3 4 5
4	Slope type	Type	Reverse Toeing Exceed incline Shorter incline Equal incline	3 1 5 2 4
5	Engineering stratum sets	Value Class Value	T ₂ b ³ T ₂ b ² T ₂ b ⁴ T ₂ b ¹ Q	1 2 3 4 5
6	Bedrock depth	m	0-3 3-5 5-15 15-30 >30	1 2 3 4 5
7	Immersed depth in 175 m water level	Value	0-10 10-30 30-50 50-80 >80	1 2 3 4 5
8	Rockmass property of 175 m-145 m water level zone	Value Class	Higher High Middle Low	5 4 3 2
9	Runoff and flood zone	Value Class	Higher High Middle Low	5 4 3 2
10	Deformation/stress concentration depth	Value m	0-10 10-30 30-50 50-80 >80	5 4 3 2 1
11	People activity	Value Class	Forest Brush/grass Cultivated land Building/road	1 2 3 4
12	Seismic dynamic parameter	Value cm/s ²	90-95 95-100 100-110 110-120 >120	1 2 3 4 5

Value 1 is the best quality, and 5 indicates the least quality.

Table 1.10 Index grades of the engineering geo-environment of Badong slope

Quality grade	Index value (Q)	Unit number	Area (km ²)	Percent (%)
Grade-1	0.0–1.5	1204	1.9264	10.77
Grade-2	1.5–1.8	2779	4.4464	24.86
Grade-3	1.8–2.4	3785	6.0560	33.86
Grade-4	2.4–3.0	2298	3.6768	20.56
Grade-5	>3.0	1111	1.7776	9.94

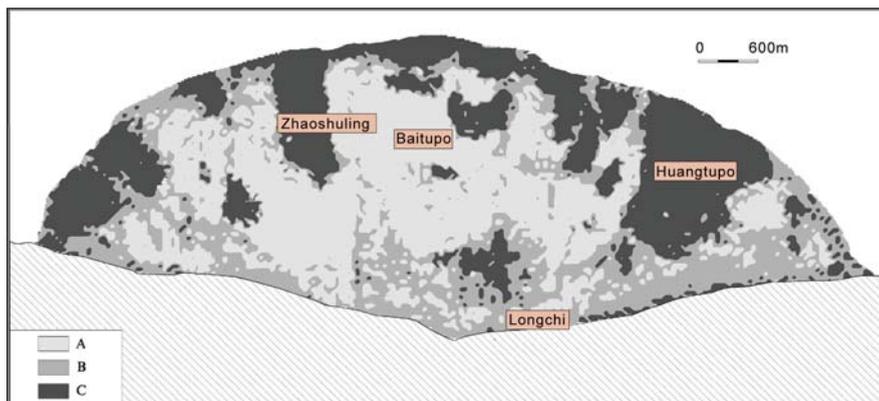


Fig. 1.20 Geological environmental function division. A – large or larger capacity; B – middle capacity; C – low or lower capacity

where the geo-environmental capacity was lower. Rock mass in zone C was unstable; there is relaxed rock mass but good quality soil, in which gardens or vegetable planting could be laid out.

Conclusions

- (1) It was feasible to advance and use the “Four degrees analysis” method for geo-hazard assessment by “distribution degree,” “potentiality degree,” “dangerous degree,” and “harmful degree” in the Three Gorges.
- (2) The ancient Chuanjiang River and the Xiajiang River linking up into Yangtze River was a great natural event, which was the principle factor forming the complex slopes. With the linking, complex bank slopes in the Three Gorges became “compound accumulation bodies,” which resulted from three strong geological actions, i.e., undercutting of headwaters erosion, “water saw” undercutting, and underwater river collapses.
- (3) The fan-shaped slope for Badong new town is a complex system. Badong complex slope system experienced sustaining gravity action, the so-called review

of gravity initiation. The action resulted from the River bank slope breakdown which produced unloading and sliding with erosion, such as sustainable hypabyssal and hypergene rebuilding, in which occurred gradual undercutting by the Yangtze River, which formed into a monoclin slope in the southern limb of the Guandukou–Dongrangkou syncline.

- (4) Geo-environmental quality evaluation and function division, at the middle or larger scale of 1:10,000–1:50,000, were helpful for town planning. The research on the Badong complex slope gave typical examples.

Acknowledgment The authors are very grateful to companies and experts for many basic survey data. They are Chongqing Nanjiang Hydrogeology and Engineering Geology Team; 208-Branch of Hydrogeology & Eng. Geology; Hubei Hydrogeology and Engineering Geology Team; Chengdu Hydrogeology and Engineering Geology Center; 915-Branch of Hydrogeology & Eng. Geology; Institute of Geomechanics, Chinese Academy of Geological Sciences; Yichang Institute of Geology and Mineral Resources, Geological Survey of China; China Aero Geophysical Survey and Remote Sensing Center for Land and Resources; Professor Ma Ganlin (Comprehensive Survey of Yangtze River Water Resources Commission); and Dr Liuxiangyu, Beijing University of Science and Technology.

References

- Aleotti P, Baldelli P, Polloni G (2000) Hydrogeological risk assessment of the Po river basin (Italy). Landslides in Research, Theory and Practice, Thomas Telford, London, pp. 13–18
- Aleotti P, Chowdhury R (1999) Landslide hazard assessment: summary review and new perspectives, *Bulletin of Engineering Geology and the Environment*, 58(1): 21–44
- Baeza C, Corominas J (1996) Assessment of shallow landslide susceptibility by means of statistical techniques. In: *Proceedings of 7th International Symposium Landslides*, Trondheim, Vol. 1, pp. 147–152
- Carrara A (1983) Multivariate models for landslide hazard evaluation. *Mathematical Geology*, 15(3): 403–426
- Carrara A, Cardinali M, Guzzetti F (1992) Uncertainty in assessing landslide hazard and risk. *ITC Journal*, 2: 172–183
- Chen XC (1993) Slope type and stability in the Three Gorges Reservoir. Sichuan Science and Technology Press (in Chinese)
- Cui ZQ (1998) Main problems of environmental engineering geology in the Three Gorge hydraulic project the Yangtze River. Study to Natural Hazards Mitigation in China, Science and Technology Press (in Chinese)
- Deng Qinglu (2000) Slope deformational structure: Badong County slope analysis. China University of Geosciences Press, Wuhan (in Chinese)
- Elliott C, Gori P (2000) National landslide hazards mitigation strategy—A framework for loss reduction. Open-file report 00-450, U.S. Geological Survey
- Geological Bureau of Hubei Province (1997) Regional hydro-geological investigation report, China (Badong Section) (in Chinese)
- Haruyama M, Kitamura R (1984) An evaluation method by the quantification theory for the risk degree of landslides caused by rainfall. In: *Proceedings of 4th International Landslides*, Toronto, Vol. 2, pp. 435–440
- He LH, Zhao H (1996) The fractal dimension of river networks and its interpretation. *Scientia Geographica Sinica*, 16(2): 124–128 (in Chinese)
- Hubei Hydrogeology and Engineering Geology Team (2001) Engineering Geologic Investigation Report of Badong Huangtupo Landslide in Three Gorges Reservoir (in Chinese)

- Koleback F, Scheidegger AE (1977) On the theory of evaluation of joint orientation measurement. *Rock Mechanics*, 9(4): 781–795
- Lee JS (1924) Geology of the gorge district of the Yangtze River (from Yichang to Tzekuei) with special reference to the development of the gorges. *Bulletin of the Geological Society of China*, 3(3–4): 351–391
- Lian JF, Liu CZ, Gao SR (2006) Research of fractal geometry characteristic on water system in gullies and valleys of Badong slope area in Three Gorges Reservoir Area. *Site Investigation Science and Technology*, 24(1): 25–28 (in Chinese)
- Liu CZ (1993a) A discussion on the engineering geology environment evolution of surface crust of the Three Gorges Project area of Yangtze River. *Journal of Hebei College of Geology*, 16(1): 56–69 (in Chinese)
- Liu CZ (1993b) The segregative characteristics of active fault system and its fractal geometry. *Hydrogeology and Engineering Geology*, 20(6): 16–19 (in Chinese)
- Liu CZ (2000) The study on development process of slope in the connected part between Chuan and Xiajiang rivers in Yangtze River. *The Chinese Journal of Geological Hazard and Control*, 11(1): 50–54 (in Chinese)
- Liu CZ, Yang B (2001) A new thought of surveying, evaluating, monitoring and forecasting for the geologic hazards in the Three Gorges on Yangtze River. *Journal of Engineering Geology*, 9(2): 121–126 (in Chinese)
- Liu CZ, Li TF, Zou ZS (2003) Geological study on the Baiyi'an landslides in the three-gorges reservoir area. *Journal of Engineering Geology*, 11(1): 3–9 (in Chinese)
- Liu CZ, Li TF, Cheng LP (2004a) A method to analyze four parameters (degree) for assessment and early warning on the regional geo-hazards. *Hydrogeology and Engineering Geology*, 31(4): 1–9 (in Chinese)
- Liu CZ, Li TF, Wen MS (2004b) Assessment and early warning for geo-hazards in the three gorges reservoir region of Yangtze River. *Hydrogeology and Engineering Geology*, 31(4): 9–20 (in Chinese)
- Liu CZ (2005) On the evolution of complex slopes in the Three Gorges of Yangtze River. *Hydrogeology and Engineering Geology*, 32(1): 1–6 (in Chinese)
- Liu CZ, Liu YH, Lian JF (2006) Initiation mechanism study on Badong slope system in the Three Gorges of the Yangtze River. *Geological Review*, 52(4): 510–521 (in Chinese)
- Liu CZ, Zhang MX, Liu YH (2006a) A System of geo-environment evaluation based on the sustainable land-use. *Geosciences Frontier*, 13(1): 242–245 (in Chinese)
- Liu CZ, Liu YH, Lian JF (2006b) Evaluation of engineering geo-environment quality of Badong large slope area in Three Gorges Reservoir region of Yangtze River. *Hydrogeology and Engineering Geology*, 33(5): 1–8 (in Chinese)
- Liu YH, Liu CZ, Li TF (2007) Numerical simulation for deformation mechanism and stability study of Badong large slope system in the Three Gorges Reservoir. *Hydrogeology and Engineering Geology*, 34(1): 47–52 (in Chinese)
- Mandelbrot BB (1982) *The Fractal Geometry of Nature*. Freeman, San Francisco
- Michael-Leiba M (2000) Quantitative landslides risk assessment of Cairns, Australia. *Landslides in Research, Theory and Practice*, Thomas Telford, London, pp. 1059–1064
- Qin Shengwu, Liu CZ, Li GJ (2006) Neotectonic stress field in Three Gorges region inverted against river system by utilizing the improved GIS method. *Global Geology*, 25(2): 160–163 (in Chinese)
- Ragozin AL (2000) *Landslide hazard, vulnerability and risk assessment*. *Landslides in Research, Theory and Practice*, Thomas Telford, London, pp. 1257–1262
- Shen YC (1965) *Valley Landform in the Upstream of Yangtze River*. Science Press, Beijing (in Chinese)
- Tian LJ (1996) *Development history of valley in the Three Gorges*. Southwest Jiaotong University Press (in Chinese)
- Yang DY (1988) The origin and evolution of the three gorges of the Yangtze River. *Journal of Nanjing University*, 24(3): 466–474 (in Chinese)

- Yang DY (2006) Landform process in Yangtze River. Geological Press, Beijing (in Chinese).
- Yangtze River Conservancy of Water Resources Committee (1997) Badong new county address in Three Gorges Reservoir geological verification report (Detailed investigation stage) (in Chinese)
- Yin KL, Yan TZ (1987) Regional landslides distribution and slope instability prediction. Earth Science: Journal of Wuhan University of Geosciences, 12(6): 631–638 (in Chinese)
- Zhang NX (1993) Consequent rock slope analysis in the Three Gorges Reservoir. Earthquake Press, Beijing (in Chinese)