长江三峡工程库岸稳定性

地质矿产部成都水文地质工程地质中心
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水利部长江水利委员会勘测总队

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内容提要

本书的基本内容是长江三峡工程库岸稳定性分析。首先论述了库岸地理地质环境特征，然后分析库岸变形破坏特征、演化规律及演化机制，并对库岸稳定性进行评价和预测，最后对库岸失稳的危害作了分析。本书可供有关专业人员及领导干部阅读。

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责任编辑　刘　云　鹤
封面设计　王　铁　麟

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《长江三峡工程库岸稳定性》

主编:田陵君　王兰生　刘世凯

编委:田陵君、王兰生、刘世凯、李昌华、李曰国、陆业海、薛果夫、陈喜昌、官泽鸿、李玉生、张年学、陈明东、王尚庆、黄金宝、谢应修、程昌和、刘成渝、盛祝平、钟阴乾、赵保安、蔡　彬、邓文玲

前　言

长江是我国的第一条大河，流域面积 180 万 Km^2，干流总长 6300Km，横贯我国东西，上经巴蜀“天府之国”，中渡两湖“鱼米之乡”，下达河口“金三角”等 18 个省、市、区，直泻东海，是得天独厚的“黄金水道”。长江三峡风景秀丽，水利资源丰富，进行合理开发，必将取得巨大的经济、社会效益，为实现四个现代化，振兴中华发挥极为重要的作用。

在长江三峡兴建大坝的构想，早在 1919 年孙中山先生在《建国方略·实业计划》中已经提出三峡“闸堰”。国内外水利界学者也曾多次策划。1949 年以后，伟大领袖毛泽东曾有过“三峡出平湖”的诗句，老一辈无产阶级革命家周恩来、刘少奇、邓小平、杨尚昆等作过多次视察。我国水利、电力、地矿、科研院校进行了大量的勘测研究和论证工作。现已确定在黄陵背斜核部南端的三斗坪兴建长江三峡水利枢纽工程（以下简称三峡工程），并提出了正常蓄水水位 175m、坝高 185m 的论证方案。库尾在重庆铜罐驿附近，干流库长 690Km。受到淹没影响的有湖北省的宜昌、秭归、兴山、巴东；四川省的巫山、巫溪、奉节、云阳、开县、万县、万县市、忠县、石柱、丰都、涪陵、武隆、长寿、巴县、江北、江津、重庆市中区及大渡口区。

三峡大坝兴建以后，具有巨大的防洪、发电、航运等经济效益。总库容为 $393\times10^8m^3$，装机容量 1768 万 Kw，年发电量 840 亿 Kw·h。这对长江中、下游，特别是荆江北南广大平原、武汉等城市及交通动脉干线免遭洪水威胁意义极大；同时对改善我国能源结构，支援华东、华南及华中经济发达地区用电，减少北煤南运的运输压力，减轻火电造成的环境污染，提高川江航运能力也有很大意义；此外，由于川江水域扩大，为养殖业和旅游业的开发也创造了有利条件。

长江三峡水库是一个典型的河谷型水库。第三纪以来该区地壳运动以缓慢上升为主，河流不断下切加宽，岸坡不断进行调整。经过多年的地质勘察工作，在干流库岸累计已发现大于 1 万 m^3 的各种类型的滑坡、崩塌及危岩变形体 283 处，总体积达 $167\times10^7m^3$。特别是近年来在三峡库区岸坡相继发生了云阳鸡扒子滑坡（1982 年 7 月）、新滩滑坡（1985 年 6 月）等老滑坡复活，黄腊石、链子崖等滑坡及危岩变形体的继续发展、更加引起了社会各界人士和国内外对三峡工程的关注，普遍认识到长江三峡这样一个世界瞩目的特大型水利枢纽工程能否建成和正常运营，充分发挥防洪、发电、航运效益，保证沿岸城镇人民的生命财产安全，除了其他方面需要科学研究论证和综合评价以外，库岸稳定性的研究也是一个十分重要的课题。

国家科委、国家计委、财政部、地质矿产部、水利部、国家地震局、中国科学院等政府部门和科研机构十分重视三峡库区的地质与地震研究工作，将长江三峡工程库岸稳定性研究列入国家“七五”科技攻关第 16 项《地质与地震》课题中的一个专题。《地质与地震》课题由地质矿产部地质环境管理司岑嘉法、楚占昌主管，长江三峡工程库岸稳定性研究这个专题的研究工作由地质矿产部成都水文地质工程地质中心负责并与成都地质学院、水利部长江委员会勘测总队共同主持。专题负责人是田陵君、王兰生、刘世凯。

长江三峡工程库岸稳定性研究工作难度较大，涉及面较广。我们从整个库岸变形破坏的实际和现今或蓄水后可能失稳、危及工程施工运营、航道畅通、城镇安全等因素出发，应用系统工程的方法，围绕攻关研究目标，对研究任务作了分解，划分为五个子专题并作了明确分工：

1. 新滩滑坡和链子崖危岩体稳定性分析、监测和防治方案研究。由湖北省岩崩研究所、长

江水利委员会三峡区勘测大队承担，研究负责人陆业海、薛果夫。

2. 三峡工程水库区岸坡类型划分及稳定性评价和预测。由地质矿产部成都水文地质工程地质中心承担，研究负责人陈喜昌(1987 年 11 月以前为李昌华、谢应修)。

3. 三峡工程库岸典型大型崩滑体形成条件、破坏机制和稳定性研究。由四川省地矿局南江水文地质工程地质队、水利部长江委员会勘测总队承担，研究负责人官泽鸿、李玉生、刘世凯。

4. 三峡库岸顺层高陡斜坡段变形破坏机制及稳定性预测。由成都地质学院、中国科学院地质研究所承担，研究负责人张年学、陈明东(前期为孙广忠、王兰生)。

5. 三峡库岸稳定性综合评价预测。由地质矿产部成都水文地质工程地质中心、成都地质学院、水利部长江委员会勘测总队承担，研究负责人田陵君、王兰生、刘世凯、李昌华。

湖北省地矿局水文地质工程地质大队、水利部长江科学院、国家地震局武汉地震研究所、武汉工业大学、中国地质大学(武汉)、西安地质学院、长春地质学院、中国科学院岩土力学研究所、中国科学院测地研究所、武汉测绘科技大学、铁道部科学研究院铁建研究所、水利部水利水电研究院水利史研究室、地质矿产部水文地质技术方法研究所等单位分别参加了有关子专题的施工、试验和研究工作。

研究工作在系统地收集了 50 年代以来地质矿产部、水电部、中国科学院、交通部、国家地震局等系统 30 多个生产、科研和高等院校等单位，开展的有关库岸的多种形式和不同规模的调查、勘探资料的同时，系统地开展了长江三斗坪至重庆江津干流及主要支流库岸的调查、研究和干流典型大、中型崩塌、滑坡、危岩体的勘探研究。在工作中采取了野外调查、勘探与室内测试并重、宏观调查与微观研究相互印证、区域定性分析比拟与点、段定量评价相结合、物理模拟与数值模拟交叉进行的技术路线与方法。野外调查采用地质测绘、钻探、坑、槽探、物探等手段，以深化对库岸和崩塌、滑坡等变形体的边界条件、结构面的空间分布地质方面的认识，为室内测试、模型的合理抽象与设计以及模拟试验的实施、数值演算分析的应用奠定坚实基础。室内试验研究除系统进行土石物理性、水理性、力学性等常规试验分析外，还应用电镜扫描、粘土差热分析、热释光温度测定等特定方法，对滑坡的滑带土、软弱结构面充填物及软弱带进行测试。并开展了岩石的流变试验、电子自旋共振(ESR)测试等，从多方面为岸坡和崩、滑体的变形破坏机制研究提供微观信息和可靠的参考依据。模型试验采用了地质力学模型、光弹模型、数值模型多种方法实现。模型设计除充分重视边界条件与参数的相似性原理外，还考虑天然水位、地下水作用、地震系数、特殊加载条件等因素的综合影响。并运用因素敏感性分析原理，对研究的段、点作出最大危险程度的评价结论。由于在国家重点科技攻关专题执行过程中做出优异成绩，于 1989 年 9 月受到国家计委、国家科委、财政部的表彰，获得颁发的集体荣誉证书。

通过上述一系列的工作，各子题分别提交了研究成果报告，专题充分利用了各子题的研究成果，于 1990 年 12 月提出了《长江三峡工程库岸稳定性研究》报告。按照专题报告提纲提供基础资料和参加编写的主要人员有田陵君、王兰生、刘世凯、李昌华、李曰国、张年学、官泽鸿、陈喜昌、黄金宝、李玉生、刘成渝、陈明东、王尚庆、盛祝平、程昌和、蔡彬、邓文玲、钟阴乾、薛果夫等。由田陵君、王兰生、刘世凯、李昌华、李曰国汇总、统编、定稿。由于在科技攻关中获得重大成果，国家计委、国家科委、财政部于 1991 年 9 月再次表彰、颁发给了集体荣誉证书。为了适应各方面的需要，扩大发行面，以利交流。经上级有关单位同意，在《长江三峡工程库岸稳定性研究》报告的基础上，经适当补充修改，以专著《长江三峡工程库岸稳定性》一书的形式出版，公开发行。本专著的工作由田陵君、王兰生、刘世凯、李昌华、李曰国等进行、最后由田陵君定稿。需要着重指出的是，参加专题攻关研究工作的工程技术人员、研究员、教授和教师、职工达

2000 余人，没有他们的辛勤劳动是不可能取得成果的，没有参加单位领导和各方面组织管理人员、职工群众的大力支持，为攻关研究工作创造良好的条件，攻关研究工作也是不可能顺利完成的。因此，本专题研究报告是集体劳动的结晶，同时也是与《地质地震课题》专家组的专家们、课题领导、课题协调办公室的精心指导分不开的。专题顾问戴广秀教授级高级工程师、张倬元教授、课题专家组组长刘广润教授级高级工程师、陈德基总工程师、胡海涛研究员和上级领导机关的岑嘉法、段永侯、郭希哲教授级高级工程师、楚占昌、魏金石、谢应修等高级工程师等自始至终都给予了很大支持、帮助和指导。柳园和赵保安工程师参加了许多工作，毛郁同志参加了部分图件、表格资料整理方面的工作，在此一并表示感谢。由于我们水平不高，不妥之处，敬请读者批评指正。

On Stability of the Bank Slopes around the Three Gorges of Yangtze River

Abstract

Yangtze River is the longest river in Chian, and the length is 6300 km from east to its whole west Yangtze River flows over 18 provinces, cities and autonomous regions, and the drainage area is $180 \times 10^4 km^2$ (about 20% of the country's land). The water conservancy resources are very rich at the section from Yichang to Chongqing of the upper reaches of the Yangtze River. If the water resources are rationally developed, considerable economic and social benefits will be obtained.

Systematic geological investigations and demonstrations on developing the resources of the Yangtze Gorges area have been conducted by Chinese geologists since 1949 especially in the last four years. Building a key hydraulic and hydroelectric project at Sandouping between Yichang and Zigui was suggested by some government and research departments (The Hydraulic and Hydroelectric Project of the Yangtze Gorges area is called as HHPYG for short in the following). The designed elevation of the dam crest is 185m, the storage level is 175m.

Ⅰ. Outline of the Geographic and Geologic Features In the Dam Area.

The reservoir area of HHPYG is located between Sandouping of Yichan and Tongguanyi of Chongqing in the upper reaches of Yangtze River. The type of the reservoir is river valley type, and the length of it is 690km. The river landscape of the reservoir area is obviously controlled by geologic structures, lithologic assemblages, and neotectonism. The east part of the dam area to Fengjie is situated in the joining place of Dabashan Wushan, and Jingshan mountain ranges. The strikes of these mountain ranges are NE-NEE, partly SE. Yangtze River bevels and transects the structure lines. The types of the river valleys are mainly insequent valleys and transverse valleys. The river vallays are narrow, and the bank slopes are abrupt. The geomorphologic land scape belongs to erosion corrosion, erosion-denudation land forms, and mid-mountain narrow valleys. The west part of the Fengjie is situated in the region being of parallel ridges and valleys and with erosion denudation low-mountain hills in the east part of Sichuan basin. The Yangtze River valley here belongs to the geomorphologic landscape of broad alternating with narrow valleys, while mostly broad valleys.

The climate of the reservoir is monsoon climate of the subtropical zone. The annual average atmospheric temperature is 16.7～18.7℃, the annual average precipitation is about 1000-1300mm, but the distribution of the precipitation on time and on space is uneven, which is more abondant in the east and mountain areas than in the west and river valleys, the water system is a dendritic water system. In the main stream section of the Yangtze River, the annual average runoff discharge is $3566 \sim 4505 \times 10^8 m^3$, and the annual average discharge is $11307 \sim 14300 m^3/s$, and floods happen mainly in July to September, and the largest discharge is $85700 \sim 71100 m^3/s$ and the smallest discharge is $2060 \sim 2770 m^3/S$. The varying range from the largest discharge to the smallest discharge is 44 to 26 times from west to east. The difference of the highest and the lowest level is 20～72m. Because the larger level range and the big rising and dropping rate of the level can cause the increased change of the groundwater level and dynamic pressure, the stability of the bank slope of the reservoir area will be affected.

Except lower series of Devonian system, upper series of Carboniferous system, some Cretaceous system and Tertiary system strata in the reservoir area, other strata were developed completely from presinia system to Quaternary system. The stratas developed from Sandouping to Miaohe section is mainly presinia system Sinia system to the middle series of Triassic system from Miaohe to Xiangqi section, mainly Triassic system to Jurassic system from Xiangi to Niukou section, the middle series and lower series of Triassic system from Niukou to Guanwuzhen section, Jurassic system from the west of Guanwuzhen to the end of the reservoir, and Triassic system and little Permian system only at the core of the anticline. The accumulation of Quaternary system distribute piecemeal on the river terraces, the planation plane, and the slopes.

The engineering geologic types of the rock and soil masses on the bank slopes of the reservoir area have been classified into four types according to their genesis, and into eight rock groups according to the structure and physical-mechanical characters:

1. Magmatic and metamorphic rock type (It has been classified into two rock groups)
2. Clastic rock type (It has been classified into three rock groups)
3. Carbonate rock type (It has been classified into two rock groups)
4. Loose accumulation type

According to the classification proposed by prof. Huang Jiqing on the China geotectonic system, the reservoir area of HHPYG is located at the SE edge of the Yangtze paraplatform, the folded belt of the Upper-Yangtze platform and the Sichuan syncline. From east to west along the Yangtze River, the structures are the Huanglin anticline with NNE trend, the NEE-NW folded belt from Badong to Fengjie, and a series of NE anticlines and synclines from Fengjie to Chongqing.

The neotectonism of the reservoir area is mainly the intermittent rising-dropping motion, and various lerels of terraces are formed. The seismic activities are faint in the reservoir area ($Ms \leqslant 5.5$ grades within 100km of the reservoir), the seismic intensity is all below 6 degree and there is no vions affection to the stability of the bank slopes.

Due to the development of the economic construction and the aggravation of human activities, the stability of the bank slopes is affected in some degree.

Ⅱ. Deformation and Failure Characteristics of Bank Slopes and Their Evolution Patterns.

The bank slopes are deformed and damaged by the exogenetic and internal geologic actions. In the reservoir area the main geologic hazards are landslides, rockfalls and deformed rock masses. According to investigation, 404 times of landslides, rockfalls and deformed rock masses of the volume over $10000m^3$ have been found along the bank slopes of the arterial stream and the main branch streams, and the total volume is $2.987 \times 10^9 m^3$. On the bank slopes of the arterial stream 283 times of landslides, rockfalls and deformed rock masses have been found, the total volume is $1.67 \times 10^9 m^3$, the average linear density of deformation and failure is about 0.205/km, and the average linear modulus of deformation and failure is about $1.09 \times 10^6 m^3/km$. Along the bank slopes of the main branch streams 121 times of landslides, rockfalls and deformed rock masses have been found, the total volume is $1.317 \times 10^9 m^3$, the average linear density of deformation and failure is 0.074/km. and the average linear modulus of deformation and failure is about $0.9642 \times 10^6 m^3/km$.

Landslides, rockfalls and deformed rock masses have been classified into four grades according to their volumes:

1. Huge scale (the volume≥100 millions cubic metres)
2. Large scale (10 millions cubic metres≤the volume≤100 millions cubic metres)
3. Middle scale (1 million cubic metres≤the volume≤10 millions cubic metres)
4. Small scale (the volume≤1 million cubic metres)

Landslides, rockfalls and deformed rock masses are the main failure types of rock masses on bank slopes, the formation parts of the slopes, and the key factors evaluating stability of the bank slopes. According to the rock structure, scale, genesis and degree of significance, detailed explorations and experiments have been made in 37 places of landslides, rockfalls and deformed rock masses with typical significance on the bank slopes.

The loose accumulation landslides are mainly formed by the transformation of landslide masses or the compound sliding of earlier landslides. The materials of the landslide mainly consist of the rock masses with spallation and cataclastic texture. There is a soil layer with various thickness on the landslide surface.

Rock-landslides are develop on the bank slopes with soft alternating with hard layer rock masses. The landslide masses consist of the rock masses with spallation texture, or cataclastic texture, or blocky texture. There is a thickness 0.2~1m thick solil layer of the glide zone on the landslide surface, and its lithology is subclay accompanied by rubble and gravelly clay. usually the landslide surface is a kind of impermeable barrier.

Rockfall is classified into slumping rockfall and falling rockfall according to its mode initial of movement. Slumping rockfalls occur mainly in the high and steep bank slope sections formed by harder carbonate rocks with flat, consequent and soft foundation. If there is a weak stratum at the base of the bank slope composed of subhorizontal strata, under the long term action of the weight of the overlying rock masses and the softening action of groundwater, the weak stratum may be squeezed out, which often results in fracturing, toppling and falling of the overlying competent rock strata. Falling rockfalls develop mainly in the high and steep bank slope sections formed by harder carbonate rocks with soft and steep-dipping foundation towards outside or inside, or develop at the core of the anticlines. when the lower soft rock layers are emptied be the river water or human activities, the upper hard rock layers will fall under the effect of gravity or vibration.

The forming condition of the deformed rock masses on the bank slopes of the reservoir area agrees with that of the rockfalls. Although the deformed rock masses are small in quantity and scale, most of them have grown into hazardous unstable rock masses, so attention should be payed to their harmfulness.

Because of the differences of geographic and geologic environments among the bank slopes, the degree of deformations and failures of the bank slopes is different on different sections stream. The bank slopes at most sections the stream have a low degree of deformation and failure so the stability of the reservoir banks is good. In the bank slopes of a few stream sections the degree of deformation and failure is serious, and landslides, rockfalls and deformed rock masses distribute intensively and the stability of the bank slopes is poor or quite poor.

The stability status, deformation and failure of the bank slopes are mainly related the geological surroundings and dynamic environment factors. The bank slopes where the landslieds, rockfalls and dangerous deformed rock masses are densely distributed consist of stratified clastic and carbonate rocks interspersed with weak seams and discontinuities, particularly, the mudrock intercalated with sandrock and carbonate rock of Middle and Upper Triassic as well as the sandrocks intercalated with weak seams of Upper Jurassic. The contact surface between the hard and soft rocks is usually argillized and its shearing-strength lowers obviously, so the deformation and failure of the rock masses is relatively intensive and dominantly massive, large-middle scale landslides. Due to the endogenic process of tectonisms, the status stress of rock masses varies at different tectonic parts. Furthermore deformation and failure are different among the bank slopes, of which the more intensive ones are mainly distributed in the segments associated with dense folds and relatively developed fractures and fissures. Moreover, the influence of geological structures on the stability of the bank slopes depend to a large extent on the combined relation ship between the running direction of river and the structure, when the river runs parallel to the axis of folds, the dip bank slopes are formed in the place where landslides occur easily, especially, in the convergent part of fold belts and on the uprising end of synclines.

Dynamic environment factors are mainly rainfalls, erosion of river water and human engineering activities. The rainfall, especially rainstorm is an important dynamic factor inducing old landslides to revive and move. The meachanism of rainstorm-induced landslides containes mainly the following: (1)rainfall saturating rock and soil masses, increasing its capacity, (2)the claysoil of slipped zone being watersaturated and its mechanica strength being lowered to a large extent, (3)infiltrated rainfalls making the groundwater table lift rapidly and flow, which produce massive dynamic and static water pressure, (4)the scarp of gullies and the slopes surface being eroded, which destroyes the integrity of rock masses, even the key part holding the balance, (5)the rainstorm in large range making the river water level lift quickly and lower rapidy after the rainstorm, causing an additional force to the bank slope, such as the decreacse of anti-sliding resistance due to undercutting of the slope base by lateral erosion, dynamic pressure resulting from the rapid lowering of the water level, etc. The erosion action of the river makes the river bed be gradually deepened and scooped out in the segment of soft rock. The lateral erosion and under cutting of slope base make the bank slope be steeper or become freeing surface so that the upper rock masses without support can be easily-sheared to move and are easy to slide when, especially, the weak intercalations were exposed in the slope base by the erosion. Human engineering activities, which were mainly located in the slope within the reservoir of the Three Gorges Project, road mainly mining, urban construction, building and unjustified cultivation, etc. These activities changed the environment of slopes, resulting in the deformation and failure of the bank slopes.

Most of the landslides distributed along Yangtze River around the reservoir of Three Gorges Project are stable or quite stable landsliding events which appeared in recent decades are mostly the revival of old ones landslides. These revival of old landslides were induced by different external dynamic factors under some certain natural geological actions. The type of the revival machinism of landslides may be summarized as follows: rainstorm induced, erosion of runoff-induced, fluctuation of water level-induced and loading-induced.

Rainstorm induced landslides: Rainstorm usually cause groundwater table to lift, forming abnormal pore pressure or dynamic water pressure and driving the slipped mass to revive.

Erosion of river induced landslides: the erosion of river water, which can not only change the shape of slopes to cause the variation of the stress status of slopes but also make the sliding plane expose directly and the free surface, presm resulting in part failure or complete revival of the slipped mass.

Fluctuation of water level-induced landslides: abnormal fluctuation of water level caused by the abrupt variation between high and low water stasons and the impoundment of the projected reservoir decreases anti-sliding resistance of the slipped mass near sliding plane in the front of landslide deposits because of lowering density, or lifting buoyancy, or instantaneous dynamic water pressure with high abnormal gradient, which revived old landslides.

Loading-induced landslides: accumulated loads resulting from rockfall mass or other mass in the top of landslides made the downward sliding—force of landslides mass exceed the anti—sliding resistance of sliding bed and revived the old landslides.

Ⅲ. Types of Bank Slopes and Analysis of Development Mechanism.

Ⅲ-1 Classification of types of bank slopes

Large number research data and information show that the factors, which control the stability of the bank slopes of Three Gorge Project, are chiefly the formation and structural characteristic of bank slopes and the combined relation between strata strike and flowing direction of river. The types of bank slopes can be divided into four main types according to engineering geological characteristics of rock and soil mass of the bank slopes.

Ⅰ Bank slopes of soil;

Ⅱ Bank slopes of clastic rocks;

Ⅲ Bank slopes of carbonate rocks;

Ⅳ Bank slopes of crystalline rocks.

Each main type can be subdivided into several types according to the texture of the rock and soil mass of bank slopes.

Type Ⅰ Can be sudivided as follows:

I_1: Bank slopes of alluvial sandy-gravelly soil;

I_2: Bank slopes of rockfall and landslide-accmulated detritus.

According to the attitude of rocks, types Ⅱ Ⅲ can be subdivided as floows:

$\mathrm{II}_1\mathrm{III}_1$: Gentle-stratified bank slopes, $\alpha < 10°$

$\mathrm{II}_2\mathrm{III}_2$: Transversal bank slopes, $\gamma \geqslant 60°$;

$\mathrm{II}_3\mathrm{III}_3$: Dip bank slopes, $\gamma \leqslant 30°$;

$\mathrm{II}_4\mathrm{III}_4$: Reverse bank slopes, $\gamma \geqslant 150°$;

$\mathrm{II}_5\mathrm{III}_5$: Oblique bank slopes, $\gamma = 30° \sim 60°$ or $120° \sim 150°$;

$\mathrm{II}_6\mathrm{III}_6$: Bank slopes with special structure, Rock mass is more fractured due to the intensive tectonic action. This type of bank slopes include the one with a weak basement. (note: γ represents the angle between the dip direction of stratified rock and the slope, α represents the dip angle of stratified rock.)

Type Ⅳ can be subdivided as follows:

Ⅳ_1: Bank slopes composed of magmatic rocks with massive structure.

Ⅳ_2: Bank slopes composed of matemorphic rock with massive-plate structure;

On the basis of the classification mentioned above, the bank slopes can be subdivided further into: gentle dip, steep dip slopes, etc. according to the dip angle of slope (β) and strata (α) of bank slopes etc.

Ⅱ-2: Development mechanism of each main type of bank slope

(1)Gentle-stratified bank slope

This kind of bank slope ($\alpha \leqslant 10°$), which is mainly distributed in gentle and broad river section, is composed of sandstone, mudstone intercalations of Middle and Upper Jurassic. Groundwater in the slopes exist as multiinterlayer water, and is concentrated usually in the contacted zone between sandstone and mudstone to cause argillization on the surface of mudstone. The bank slope is geomorphologically, situated at hill country, and take a stepliked form. The step scarps are usually composed of sandstone and are several to several tens meter high the step surface are generally composed of mudstone. The stability of bank slopes depends to a large extent on the engineering feature of mudstone strata and anti-sliding characteristic of the contact surface between sandstone and mudstone as well as the shape of slopes. The deformation and failure of bank slope occurred predominantly at spurs. Its developing process, can be summarized as follows: plastic flowing failure, shearing failure and horizontal-push-sliding failure.

Plastic flow failure: the failure is developed from the deformation of plastic flow-tensile fracturing in a certain broad and gentle slope composed of stratified rocks of which upcovering sandstone mass can be dissected and destroyed because underlaying mudstone mass can be dissected and destroyed, as underlaying mudstone mass is dissected by the plastic flow-tensile fracturing.

Shearing failure: the failure is developed in mediately dip slopes composed of sandstone and mudstone intercalations because a step connected-zone was sheared, and is mostly little — scale oblique landslide.

Horizontal-push-sliding failure: the failure is induced by the combined actions of the static water pressure in fissure with the buoyancy in potential slipping surface resulting from an abnormal water level during rainstorms.

(2)Dip bank slopes composed of stratified rocks.

This kind of bank slope is composed of Jurassic clastic rocks composed dominantly of sandstone and mudstone with the height of hundred to several hundred meters. The shape of the bank slope are obviously in the control of lithologic charater and structure, most of which are equivalent dip slope or reverse dip slopes (reverse steped slope) and undulating dip slope appears only in the sections with genile dip (dip steped slope). Meanwhile, slope shape and character determined the concentration and strength of precipitation and dynamic feature of groundwater in slopes. The studies show that the development mechanism is related to the structural types of the bank slope, and can be summarized as follows:

Sliding failure is mainly developed in stratified slopes in which the strata dip is 10°～20° and 20°～40° or steep in the upper and gentle in the lower under the condition of the exposure of weak slipped surface due to the undercutting of slope base. The forming condition and developing mechanism can be divided into sliding falling, slow slidingtensile fracturing and rotating sliding—tensile fracturing.

Shearing failure is caused by the exposure of sliding surface due to the undercutting, and developed in middle to steep dip bank slope composed of stratified rocks.

Sliding-bending failure is mainly developed in middle dip slope and chair-liked slopes composed of stratified rocks, and can be divided into three stages: gentle bending, intensive bending and connecting of sliding surface, sliding-failing.

(3)Reverse bank slope composed of stratified of rocks.

The bank slope are composed of the sandstone and mudstone of Jurassic and ones intercalated with carbonate rocks. Groundwater is concentrated usually in the weakened zone of bank slope. Bank slopes are stable, but a certain number of small-scale rockfalls and landslides were developed in high and steep bank slopes. and larger scale and oblique landslide occurred at one or two slopes.

The development mechanism of the reverse dip bank slope composed of stratified rocks can be summarized as follows:

(Ⅰ)Toppling deformation it appears in the bank slopes with dip angles of 40°～50°. Because rock masses may be dissected by a steep dip fracture perpendicular to bedding plane, ther can topple or fall when the slope base suffer lateral erosion.

(Ⅱ)Bending-tensile fracturing appears in the bank slope composed of brittle rocks in which the strata dip into slope with a dip of 30°～60° and intersect at an acute angle with slope surface. The deformation develops gradually from surfacial to deep and cause the tensile farcturing of the rear rocks and the breaking and shearing of the root rocks.

(Ⅲ)Creep sliding-tensile fracturing. When the deformation mentioned above develops to a certain degree, the gradual accumulated failure occurrs in the part where strain energy exceeds the strength of rock masses, gardually extends the deformation and connect the slipped surface, and at last cause a large scale landslide whose arcuate slipped surface to cut through the strata.

(4)Bank slope composed of carbonate rocks

Carbonate rocks along Yangtze River in the reservoir of Three Gorges Project is mainly exposed in deep valley area and forms high, steep bank slope. When there is a thick weak stratum or seam in the base no rocks or between rocks, bank slopes are stable. The landslides, rockfalls and dangerous deformed rock masses in this kind of bank slope usually occur in the sections where the upper is composed of hard carbonate rocks and the lower soft strata. The mechanism of deformation and failure of the slopes can be mainly divided into three kinds i. e. falling, toppling and sliding pattern.

Ⅳ Evaluation and Prediction of the Stability of Bank Slopes.

The evaluation and prediction of the stability of bank slope include (A) the stability of the remains after landslids and rockfall (B) the stability of bank slope. These two aspects are related and complemental to each other, and play an important role in the stability of bank slope. Furthermore, it must be emphasized to study the statu of the bank slope and the remains of landslides and rockfalls, and predict the stability of them after the impoundment of the projected reservior or under a certain special condition when evaluating and predicting the stability of all bank slopes.

In the research, geological analysis, probability statistical analysis and calculation stability are, made on the basis of the obtained data and information, incorprated to form a perfect and tight system to carry out the evaluation and prediction, including the following:

Ⅳ—1 Evaluation and prediction of the stability of the remains of Landslides and rockfall

Special explorations and tests have been used in large scale and typical landslide and rockfall during the research. On the basis of the works mentioned above, geological analysis can be made on the relation between landslide. Rockfall and the character of themselves, dynamic factors of surroundings. Then, foremost factors controlling the stability of landslide and rockfall can be determined with the help of the calculation of stability and the probabilistic analysis and then proceed to comprehensively evaluate and predict the stability of all bank slopes.

(1)Geological analysis on the stability of landslide and rockfall: Through a systematic analysis to exploring and testing data on landslide and rockfall, geological signs should be recognized by which the influence of contour, structural characteristic, and environmental factors on the stability can be distinguished. The characteristic of contour contains mainly average slopes, status of freeing surface in the rear of landslides and rockfalls, degree of cutting valley and state of slosed basin which can influence the stability quite seriously. Structural characteristic is mainly the shape feature of sliding surface and the feature of rocks and soils in the remains of landslides and rockfalls. The shape feature of sliding surface include average dip, its shape, antisliding ratio(ratio of the length of antisliding section to the whole length of sliding surface). The feature of rock—soil in landslide and rockfall remains can be divided into three type: loose, disintegrated and blocked structure to reflect whether or not it is easy permeating and draining in the remains. Environmental factors contain mainly lateral erosion of river, special climate, additional loading in landslides, earthquake and human engineering activities.

(2)Probabilistic quantitative analysis: probabilistic analysis of failure, sensitive analysis of stability and fuzzy comprehensive assessment, etc, have been applied to systematically analyze and evaluate a large scale and typical landslide and rockfall, calculate the resulting probability of stability, and make a quantified analysis on the influence of various distinguishing signs of geology on stability.

(3)Calculation of stability: The limiting eguilibrium stability has been calculated for a large—scale, typical landslide and rockfall for which there have been detailed data. A thrusttransmitted coefficient has been taken as a dominant method and associated with other calculation methods in the calculation. Except for the self—weight stress of landslides and rockfalls, dynamic water pressure, and bouyancy of groundwater have also been considered, and earthquake effect has been checked.

(4)Comprehensive evaluation and prediltion: Three methods mentioned above were incorporated. Stability analysis on landslides and rockfalls with detailed exploring and testing data were made, by the system, to get assessing results more suitable for practice. In addition, the system was applied. to evaluate the stability of landslides and rockfalls in the area without detailed geotecnnical testing data and obtained a satisfactory results.

There are 24 massive, 13 middle scale landslides and rockfalls which were explored and tested along the bank slope in the reservior of Three Gorge Project. All the deposits of landslide and rockfall are stable or basically stable at low and normal water level before the impoundment of the reservior of the project, but Hang lashi, Sandengzi, Xiangjiawan, Qianciaotuo, Western Yunyang, and Longwangmiao old landslides and Yaqianwan rockfall are unstable when a flood is met in one hundred years and continuous rainfall, rainstorm occur in local area. After the impoundment of the reservior, the stability of all old landslides and rockfalls will be similar to one in flood water level met in one hundred years during continuous rainfall or rainstorm in local area, or at flood—controlled, limited water level. Expect Qianciaotuo, landslide whose stability is not good, the others will be stable or basically stable at normal water level of the impoundment (175m) and without abnormal fluctuation of water level in dry season.

Ⅳ—2 Evaluation and prediction of the stability of band slopes

(1)Classified assessment of bank slope

According to the classification criteria and geological signs of the development mechanism of bank slope, the stability of the main kind band slope was assessed.

(2)Probabilistic quantitative analysis on the stability of band slope

The influence of various key elements of slopes and environmental dynamic factors on bank slope were quantitatively analyzed by the mathematic methods of probability and statistics, such as message methods, multi—factor methods, to make a combination and evaluation of stability band slope.

(3)Analysis of the developing mechanism in important bank slope and quantified evaluation and prediction the stability.

Ⅳ—3 Comprehensive evaluation and prediction on the stability of band slope

Summing up the evaluation and prediction result mentioned in 4. 2 and 4. 1 with reference to marking assessment by experts, evaluation and prediction were made on the stability of bank slope of each river section.

(1)The band slopes are rather stable along the mainstream of Yangtze River. In Three Gorges Project, 95% of the bank slopes are stable and basically stable before and after impoundment. And bank slopes with poor and not good stability are about 53. 8km long and only makes up 3. 9% of the whole bank slopes before the impoundment.

(2)The impoundment has no important influence on the stability of the bank slopes. Lianziya and Daping-Huanglashi sections which account to 5. 5km long are bad in stability before and after the impoundment. There are 8 sections of bank slopes which account to 48. 3km and are not good in the stability before the impoundment. The number will be up to 65. 8km after impoundment, increasing 12km mostly in the urban slope of Chongqing city.

The bank slopes with poor and not good stability mentioned above are mostly the ones in which landslides, rockfalls, and dangerous deformed rock masses are densely distributed. It's predicted that the movements and failures of bank slopes will mostly be caused by the revival of old landslides and rockfalls as well as unstabilization of dangeous deformed rock masses

Ⅴ. Harmfulness prediction and control to the failure of bank slope.

Ⅴ—1 Harmfulness analysis to the failure of bank slope

The harmfulness of the failure of bank slopes along Yangtze River around the three Groges Project is manifested mainly by the influence on the building of the key proiect, storage capacity, life expectancy, shipping of the reservoir, safety of cities and towns along the bank, planning of migration, and siting of cities and towns, etc.

(1)The influence on the construction and utilization of Three Gorges Project

Large scale landslide and the bank slope with bad and not good stability are domjnantly over 25km away from the dam—site of sandouping movement and failure or revival of old landslides ean not make direct harm to the construction and utilization of the project. The rising wave from the masses sliding into the river will not exceed 2-3m high when it reach at the dam—site, so it will not form a serious menace to the dam and construction coffer.

(2)The influence on the storage capacity of the reservoir

There are 404 landslides and rockfalls whose volume is over ten thousands m^3. Total volume of all the landslides and rockfalls will be 2.987 billion m^3 which only makes up 7.5% of the total storage capacity of the reservoir $393\times10^8m^3$ at normal water level (175m) of impoundment of the Three Gorge Reservoir. Among them, there are 59 large and middle—scale landslides and rockfalls with bad and not good stability whose volume is 0.4 billion cubic metres. If , according to a high estimation 12.5% of the whole movement of slopes slide into the river, which makes up 0.2% of total storage capacity of the reservoir. So, landslide, rockfall and collapse is not a main source of deposits of the reservoir, so that has no essential influence on the life expectancy of the reservoir.

(3)The influence on shipping

The landslides and rockfalls slipping into the river block the shipping in different degrees at low—water season. If Lianziya and Huanglashi landslides move into the river at high water season or in initial stage of utilization of the project a certain influence on shipping will also be exerted. Because the river will widen and deepen at normal water level of the impoundment, landslides and rockfalls sliding into the river will not seriously blodk shipping. But, the harm resulting from the rising wave caused by the landslide and rockfall into the reservoir. In influenced range to the shipping should not be ignored.

(4)The influenec on cities and towns and migration

The landslides and rockfalls in the bank slope with bad and not good stability will influence, directly or indirectly, the migartion of local people and the movement of cities and towns along the Yangtze River.

V—2 Protecting measures against the failure of bank slopes.

Studying result of Xintan and Jibazi landslides shows that landslides undergo a rather long process of deformation before sliding. Each of the large and middle—scale landslides and rockfalls, with bad and not good stability, have a volume of 340 million m^3. It is highly estimated that there is 12.5% of the whole unstabilzaition with 42 million m^3 in volume, in additional to 70 million m^3 of soil landslide deposits. Furthermore, by means of detailed exploration tests and long—term observation to the landslides and rockfalls, it is possible to predict the time and place of the movement of bank slope and landslides and rockfalls. An indispensable harness can also avoid and decrease the harm of the movement of slope.

(1)Protecting principles: Based on the reality of the Three Gorges Project, protecting work should comply with the following principles