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ENGINEERED SLOPES IN CHINA
– Approaches and Case Studies

中国典型工程边坡

Water Resources and Hydropower Volume

水利水电工程卷

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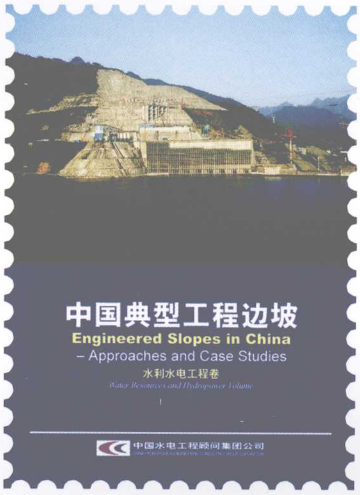

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序言

我国相当一部分国土处于崇山峻岭，遭受的滑坡和泥石流灾害十分严重。正在进行的大规模重大工程建设中的边坡稳定问题也至关重要。矿山、水利以及交通工程中发生的滑坡灾害带来了巨大的人员伤亡和财产损失。与此同时，三峡、小浪底以及青藏铁路等工程的成功建设也积累了大量的宝贵经验。

致力于减轻地质灾害和边坡工程研究的中国工程师和学者非常荣幸有机会主办2008年第10届国际滑坡与工程边坡会议。经讨论，我们决定出版有关中国滑坡和工程边坡的两个姐妹画册。中国典型滑坡画册由殷跃平博士主编，于2007年12月出版。中国典型工程边坡画册分别包括矿山工程卷、交通工程卷、水利水电工程卷及三峡库区卷。现在，我们非常高兴地看到，在各位同仁的共同努力下，该系列画册的出版已经成为现实。

本系列画册描述了工程建设中的一些重要的滑坡实例。盐池河滑坡和韩城电厂地面变形是由于地下开采引起的两个典型例子。前者掩埋了一个村庄，导致284人死亡；后者对边坡的变形和破坏影响持续了20年之久。由开挖引起的滑坡失事比较普遍。天生桥二级、小湾及漫湾等水电工程的教训值得我们重视。千将坪滑坡是三峡水库蓄水后的一次失事实例，尽管128人成功撤离，但仍导致了24人死亡。还有大量的位于黄土地区、寒冻土地区和沙漠地区的公路与铁路边坡，独具中国特色。

该系列画册还包括了若干成功的重大工程边坡实例。三峡船闸高边坡开挖石方量达$22\times10^6m^3$，应力释放问题受到普遍关注，争论热烈，现在已经得到了答案。小浪底进、出口边坡位于第三纪砂岩与厚黏土夹层之上。在这个边坡布置了165m高土石坝的全部引水系统，施工期及运行期的成功运用，对这个黄河上的主要工程的安全极为重要。锦屏拱坝高达304m，开挖深度达530m，边坡坡度陡峻，达1：0.5～1：0.3。读者还会惊叹于那些描述三峡工程120万移民新城镇的图片。为了确保这些边坡的安全，我们做了大量的工作。

我们真诚地感谢国务院三峡工程建设委员会办公室、中国水电工程顾问集团公司、中国矿业大学（北京）以及中交第一公路勘察设计研究院有限公司提供的经济资助以及在收集资料方面所做的努力；特别感谢那些提供宝贵图片和文档的人员，虽然不能在此一一列出他们的名字；特别感谢谭国焕教授、岳中琦教授、吴宏伟教授和殷建华教授，是他们组织人员进行了翻译；特别感谢苏宝纨女士，她和她的助手们志愿翻译了四卷画册的中文。没有他们的努力，该画册英文内容的出版几乎是不可能的。

陈祖煜

凤懋润

Foreword

With its large and mountainous topography, China has suffered from serious landslide and mudflow hazards. The large-scale economic construction has also raised serious slope stability concerns. Catastrophic landslides happened in the engineered slopes created in mining, hydropower and transportation projects, bringing huge losses of human lives and properties. On the other hand, valuable experiences have been obtained from many successful engineering slopes such as those involved in the projects of Three Gorges, Xiaolangdi, and the Qinghai – Tibet Railway, etc.

The Chinese engineers and scholars working on geohazard mitigations and slope engineering are particularly privileged to have the opportunity of hosting the 10th International Symposium on Landslides and Engineered Slopes in 2008. After a warm discussion, we decided to publish the sister-volumes of albums entitled 'Landslides in China – Selected Case Studies' and 'Engineered Slopes in China – Approaches and Case Studies' respectively as gifts to the Symposium. The landslide volume was edited by Dr. YIN Yueping and published in December, 2007. This 'early bird' brought great pressure and encouragement to us who had taken the responsibility of compiling the latter, an even big collection that consists of 4 volumes concerned with slopes of mining, highway and railway, water resources and hydropower, and the Three Gorges Reservoir projects respectively. We are happy to see that this album has now come to reality as a result of the joint efforts made by our colleagues working on different industrial and civil areas.

This album describes some important slope failure cases in engineering. The landslide of Yanchihe and the large ground movement of the Hancheng Power Plant are typical examples of slope failures induced by underground mining. The former buried a village and killed 284 people, and the latter caused more than 20 years sustaining slope movement and damages to the power plant. Landslides triggered by excavations are common and the slope failure cases of Tianshenqiao II, Xiaowan and Manwan projects are certainly worthwhile to be studied. Qianjianping Landslide is one case of slope failure caused by filling of the Three Gorge reservoir. Although 128 people had successfully evacuated, it still resulted in 24 fatalities.still many engineered slopes on highways and railways in the area of loess, frozen soil and deserst are specific in China.

This album contains a number of large-scale successful engineered slopes. The navigation lock of the Three Gorges project involves an excavation of $22\times10^6 m^3$ rocks and the issue of stress release had been a serious concern, to which the answer is available now. The intake and outlet slopes of the Xiaolangdi Project were built in Tertiary inter-bedded sandstones with thick clay seams. As these slopes accommodate all water diversion facilities of this 165 m high embankment dam, the successful performance during construction and operation has been a great contribution to this key project in the Yellow River. The left abutment of the 304 m high Jinping arch dam necessitates a 530 m deep excavation with a sloping of 0.5~0.3 (H) on 1 (V). Readers will also be impressed by the pictures that describe the new cities for the 1.2 million resettlement people of the Three Gorges Project. Tremendous efforts have been made to ensure safe performance of these slopes.

We would like to extend our sincere thanks to Office of Three Gorges Construction Council under the State Council, China Hydropower Engineering Consulting Group Corporation, China University of Mining & Technology, Beijing and CCCC First Highway Consultants Co., Ltd for their financial support and efforts in collecting all the necessary information. Special thanks also go to those who offered their valuable photos and documents. To mention them one by one appears to be impossible, but their contributions will be remembered. We are particularly indebted to Professors George Tham, Zhongqi Yue, Charles Ng, and Jianhua Yin from Hong Kong, who organized the English translation work. We are especially grateful to Mrs. So Po Yuen, Cynthia, who edited the English language voluntarily for all the 4 volumes based on her technical assistant's work. Without their effort, the English texts of this book would not have been made possible.

CHEN Zuyu

FENG Maorun

前言

在水利水电工程建设和运行中，滑坡体和边坡是重要的危险因素，严重威胁水利水电枢纽工程安全，若防范不当，可能造成人们生命财产的重大损失。随着水利水电建设事业的进一步发展，边坡稳定及其危害性问题也越加突出。

与公路边坡、铁道边坡、矿山边坡、民用建筑边坡相比，水利水电工程边坡有其特殊性、复杂性。因地处深山峡谷，地形地质条件复杂，加上枢纽建筑物布置要求，水利水电工程边坡开挖深、高度大、处理难度高，是其他行业边坡工程中难得一见的。

近30年来，我国水利水电工程建设取得了世人瞩目的成就，水利水电工程技术也获得了长足的发展，整体上达到世界先进水平。水利水电工程边坡地质勘察评价、变形稳定分析、设计、施工和运行管理均积累了丰富的经验，可供其他行业所借鉴。

我国水利水电工程边坡及其工程技术具有以下特点：

(1)边坡工程规模大。开挖边坡高度从20世纪80年代的百米级，发展到现在的数百米级，开挖边坡体积从数十万立方米、数百万立方米，增大至数千万立方米，开挖边坡的水平深度从十数米、数十米级，增大到上百米，甚至数百米级。

(2)边坡地质条件复杂。不仅有各种复杂成因、物质组成、工程特性的覆盖层边坡或滑坡体，而且还有各种复杂结构和构造以及各种风化卸荷程度的岩质边坡；不仅有各种不同变形、稳定状态的边坡或滑坡体，而且还涉及高地应力、高地下水位以及各种复杂作用。

(3)边坡的稳定性至关重要。水利水电枢纽工程选址取决于诸多因素，坝基及两岸边坡工程地质条件是枢纽选址的主要影响因素之一，边坡稳定安全性不仅关系工程安全、建筑物安全，而且对工程造价和施工工期也有重要影响，与枢纽总体布置和建筑物设计关系密切。

(4)边坡设计和施工要求高。要在查明或基本查明边坡工程地质条件的基础上，分析评价边坡稳定状态、影响边坡稳定性的主要因素，预测可能的发展变化趋势，综合考虑施工期、运行期各种作用和边坡岩体、滑坡体物理力学特性的可能变化，边坡失稳的可能影响，研究提出边坡设计方案及相应的施工技术要求。

(5)数值解法得到普遍应用。基于岩体力学、计算技术的发展，数值模拟解法，如有限元法、边界元法、块体单元法、离散元法以及不连续变形分析法等广泛应用于水利水电工程边坡或滑坡体的变形和稳定性分析，依据重大工程，开展多方面深入的科学研究，进一步加深了人们对边坡、滑坡体变形失稳破坏机理的认识，提高了治理边坡的有效性。

(6)治理措施针对性强。按照"安全可靠、经济合理、技术先进、环境友好"的设计原则，提出了"治坡先治水"的设计思想。边坡开挖加固处理中，控制爆破、预加固、锚喷支护、抗滑桩、混凝土回填、固结灌浆等措施选择余地大，灵活多样，针对性强。防渗排水体系、安全监测体系成为高边坡治理中必不可少的组成部分。

(7)边坡勘察设计和施工规范化。总结以往水利水电工程边坡勘察设计施工科研工作成果和借鉴国内外其他类似工程经验，建立了水利水电边坡工程设计和施工标准，包括《水电枢纽工程等级划分及设计安全标准》（DL 5180）、《水电水利工程边坡工程地质勘察技术规程》（DL/T 5337）、《水电水利工程边坡设计规范》（DL/T 5353）、《水电工程预应力锚固设计规范》（DL/T 5176）和《水电水利工程锚喷支护施工规范》（DL/T 5181）等。

(8)勘察设计和施工管理手段现代化。随着地质勘察技术、数值分析方法、计算机技术、网络技术和信息技术的发展，水利水电工程边坡勘察设计和施工管理正在加速信息化进程，多专业协同、三维可视化、动态设计与施工、精细计算和快速反馈等使得水利水电工程边坡勘察、设计和施工管理一体化成为可能，提升了边坡处理的现代化水平。

为祝贺第10届国际滑坡与工程边坡会议2008年6月30日至7月4日在西安召开，丰富工程边坡和滑坡体治理知识宝库，加强国内国际交流与合作，促进边坡工程技术共同发展，第10届国际滑坡与工程边坡会议组织委员会决定，由相关行业权威部门编制出版《中国典型工程边坡》画册，共分交通、水利水电、矿山工程和三峡库区四卷。

中国水电工程顾问集团公司主编水利水电工程卷。该卷收录了已建、在建工程8项典型边坡案例，包括南盘江天生桥二级水电站厂房高边坡、澜沧江漫湾水电站左岸坝肩高边坡、黄河小浪底水利枢纽进出口高边坡、长江三峡水利枢纽船闸高边坡、乌江洪家渡水电站左坝肩及进水口高边坡、红水河龙滩水电站左岸坝肩高边坡、澜沧江小湾水电站左岸堆积体高边坡、雅砻江锦屏一级水电站左岸坝肩高边坡等。

《中国典型工程边坡 水利水电工程卷》收录的高边坡工程，安全标准高、地质条件复杂、设计和施工均有相当难度，基本反映了当代中国水利水电工程边坡处理技术的水平、风格和特点。案例除简要介绍工程概况外，重点反映边坡的基本地质条件、变形稳定或滑动状况、主要处理措施和运行监测情况等，并以大量图片真实地反映了工程建设过程和目前状况。

本图集在编辑过程中得到入选工程的建设单位和设计单位的大力支持。在此，深表致谢。由于编辑时间仓促和编者水平有限，不当和错误之处，恳请广大读者批评指正。

周建平

2008年5月

Preface

There are many large slopes with great height and very complex geological and hydrological conditions in China's water resources and hydropower projects. Slope stability problems greatly influence the feasibility study, investment, decision-making, construction and safe operation of these projects. Slope failures have caused serious damage to human lives and properties. With the rapid development of China's hydro-projects, slope stability had become an important concern.

Compared to the engineering slopes of other areas such as mining, highway and railway, hydro-projects involves even more complexities as these slopes are normally high and steep, located in deep valleys with complicated geological and topographic conditions. The requirement for aligning various hydraulic structures presents more challenges. It is therefore worthwhile to pay special attention.

In the past 30 years hydro-project slope engineering techniques have made great achievements, and have already established a complete set of technical standards including reconnaissance, design, construction, instrumentation and management. In this volume we would like to share these experiences with our peers.

Design and construction of hydro-project slopes are featured in the following aspects:

(1) Very large scale. The excavation height of slopes have extended from an order of 100 m of the last century to several hundreds currently, and the excavation volume, from several hundred thousand cubic meters to millions, or even tens of millions.

(2) Complicated geological conditions. Hydro-project slopes often encountered various kind of landslip masses with complicated formation, as well as different kind of rock structures, ground water levels and high in-situ stresses.

(3) Very high safety requirement. The impact of a slope failure can be very critical to the whole hydraulic scheme. Great loss of human lives and properties can be incurred if a landslide ever happens.

(4) High requirement for design and construction. It is necessary to have detailed geological exploration to assess the stability status of the slope, to identify the main factors that may trigger instability, and to predict its performance. With a comprehensive consideration of various operation stages and possible changes of physical and geotechnical parameters, the rational design and construction will be conducted.

(5) Extensive use of various numerical approaches. Applications of advanced rock mechanics and analytical approaches include the finite element; discrete element; boundary element and key block methods. A number of scientific research projects have been carried out for some large hydropower projects, which gave enlightening insight into the failure mechanism and ensured the effectiveness of various stabilizing measures.

(6) Effective reinforcement measures. The correction principles are: 'reliably safe, economically rational, and environmentally friendly'. It was also emphasized that treating water should always be placed at top priority.

(7) Standardization of design and explorations. By summarizing the experiences obtained from the geological explorations and design of a series of engineered slopes, as well as those from similar areas in China and overseas, a number of design and construction codes and standards have been published. They include the standards for classification and gradation of hydropower projects (DL 5180), and for geological reconnaissance and explorations (DL/T 5337); the codes for hydropower slopes design (DL/T 5337), for pre-stressed anchoring (DL/T 5176), and for shotcrete constructions.

(8) Advanced design and construction tools. The slope engineering exploration, design and construction have been greatly benefited from the advanced geological investigation technologies, numerical methods, web and information based techniques. They include the coordination of multiple-majors, 3D visualizations, dynamic design and construction approaches, precise design and fast feedbacks, etc.

In commemoration of the 10th International Symposium on Landslides and Engineered Slopes, to be held in Xi'an, China from June 30 to July 4, 2008, the Organizing Committee has decided to publish the photo albums entitled 'Engineered Slopes in China - Approaches and Case Studies' edited by authorities from the mining industry, railway and high way engineering, water resources and hydropower engineering, and the Three Gorges reservoir resettlement administration. This work will by all means enrich our knowledge of slope engineering and landslide mitigations, enhance the collaboration of various disciplines of our country and promote international exchanges and co-operations.

This volume is edited by China Hydropower Engineering Consulting Group Corporation. It includes engineered slopes of 8 typical hydro-projects. They are the navigation lock of Three Groges, intake and outlet of Xiaolangdi, left bank and abutment of Hongjiadu, power plant of Tianshenqiao II, intake of Longtan, and left abutments of Manwan, Xiaowan, and Jinping.

The engineering slopes selected into this volume feature in their high requirement for safety and complex geology, resulting in a number of challenges in design and construction. In essence, they represent the state-of-practice of China's water resources related engineered slopes in terms of expertise, style and characteristics. The large number of pictures vividly shows the construction and performance of these slopes, in addition to the descriptions of their geological background, deformation and failure process, reinforcement work and monitoring.

The editors of the volume wish to extend their sincere thanks for the supports given by the designers, owners and contractors of various projects. Comments from the readers will be highly appreciated.

ZHOU Jianping

2008.5

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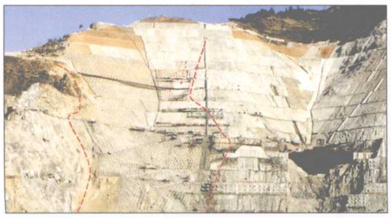
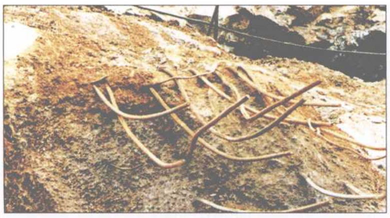


中国典型工程边坡

Engineered Slopes in China

– Approaches and Case Studies

水利水电工程卷

Water Resources and Hydropower Volume

中国水电工程顾问集团公司

CHINA HYDROPOWER ENGINEERING CONSULTING GROUP COPORATION

1 南盘江天生桥二级水电站厂房高边坡

图1.1 天生桥二级水电站高边坡全貌

Fig. 1.1 An overview of the high slope of the Tianshengqiao Grade II Hydropower Station

主要技术特点：

- ▲ 西坡和南坡属典型层状高边坡，厂房开挖施工过程中出现顺层错位和倾倒破坏，采取排水、喷锚和贴坡墙进行了处理。
- ▲ 下山包古滑坡体在厂房开挖切脚后出现了大面积滑坡，采用减载、地下排水洞、抗滑桩、预应力锚杆、预应力锚索、钢筋桩、钢筋混凝土框架护坡等综合措施进行治理。

Main characteristics

- ▲ West Slope and South Slope are layer high slope. During the construction of the plant, there were occurrences of slop toppling and original position displaced. Many measures were taken to enhance safety such as grouting and anchoring, drainage, and retaining walls.
- ▲ In order to prevent slope failure, comprehensive measures have been taken to stabilize the Xiashanbao landslide in the form of load reduction, underground drainage holes, slope stabilizing pile, pre-stressed soil nails, pre-stressed cables, steel bar reinforced piles and steel bar reinforced concrete frames.

1.1 概述

天生桥二级水电站位于广西和贵州界河南盘江下游，距贵阳市直线距离230km。工程开发任务为发电，水库正常蓄水位645m，总库容0.88亿m^3，装机容量1320MW。枢纽工程由首部挡水建筑物、泄水建筑物和进水口、长引水隧洞及地面厂房建筑物等组成。混凝土重力坝，最大坝高60.7m，3条内径8.7~9.8m的引水隧洞平均长度10km，利用河段水头落差180m。地面厂房后边坡稳定性差，施工期曾发生滑动，采用了多种措施进行综合治理（图1.1和图1.2）。

1.2 工程地质

天生桥二级水电站厂区边坡总高度380m，上部120m为调压井边坡，下部260m为厂房边坡。厂房边坡由西坡陡岩、芭蕉林滑坡体、西坡及南坡4部分组成（图1.3），另外，在厂房西坡顶部有下山包滑坡体。厂房边坡自北向南主要构造迹线为中山包背斜、芭蕉林向斜、下山包背斜及拉线沟向斜（图1.4）。

图1.2 完成治理后的调压井边坡及厂房边坡正面

Fig. 1.2 Surge shaft slope and plant slope after treatment

1 High Slope of Tianshengqiao Grade II Hydropower Station, Nanpan River

1.1 General

Tianshengqiao Grade II Hydropower Station is located in the lower reaches of the Nanpan River at the boundary between Guangxi and Guizhou Province. Its geographical distance from Guiyang is 230 km. The total volume of the reservoir is 8.8×10^7 m^3 and normal pool level is 645 m. The station's maximum power production capacity is 1,320 MW. The key structures include the head structures, the guidance long-term current system and the ground surface plant. The concrete gravity dam is 60.7 m high, with three water diversion tunnels with inner diameters ranging between 8.7 and 9.8 m, and an average length of 10 km. The water head difference available is 180 m. This hydropower station project is classified as mega scale.

The occurrence of landslides on the engineered slope behind the plant during excavation led to comprehensive measures to improve slope stability (Fig. 1.1 and Fig. 1.2).

图1.3 厂区枢纽布置及边坡示意图

Fig. 1.3 Plan of the key buildings and the distribution of slopes

1.2 Engineering Geology

The excavated slope at the Tianshengqiao Hydropower Station reaches a height of 380 m. The upper 120 m of the slope is the surge shaft slope, while the lower 260 m is the plant slope. The plant slope comprises West Steep, Bajiaolin Slide Body, West Slope and South Slope (Fig.1.3). In addition, the Xiashanbao landslide can be found at the top of West Slope. The main geological structure line of the plant slope from north to south is Zhongshanbao anticline, Bajiao syncline, Xiashanbao anticline and Laxiangou syncline (Fig. 1.4).

1.2.1 西坡

厂房西坡为岩质边坡，至基坑底部，坡高164m，其中永久边坡高124m，临时边坡高40m，岩层平缓。分布地层主要是江洞沟组T_{2j}^{4-1}～T_{2j}^{5-2}层砂岩夹泥页岩及少量薄层灰岩。由于构造裂隙的切割，形成层状裂隙化岩体（图1.5）。

厂房西坡在开挖过程中，地应力调整、变形导致炮孔错位，地应力调整结束后，错位现象即结束。

1.2.2 南坡

南坡至厂房基坑底部坡高70m，其中永久边坡高30m，临时边坡高40m，属反倾向薄层砂页岩互层边坡，以倾倒破坏为变形特征。分布江洞沟组T_{2j}^{5}层砂岩夹泥页岩，岩层倾向坡内，倾角60°左右，组成逆向坡。开挖后的边坡坡比（*V*∶*H*），一般为1∶0.8～1∶0.5。在施工期的4个月中，先后3次发生岩层的倾倒破坏（图1.6）。

南坡发生倾倒破坏后，治理措施包括调整边坡开挖坡比，挖除全部的倾倒破坏岩体，进行喷锚支护和设置排水系统，在低高程采用贴坡钢筋混凝土挡墙等。

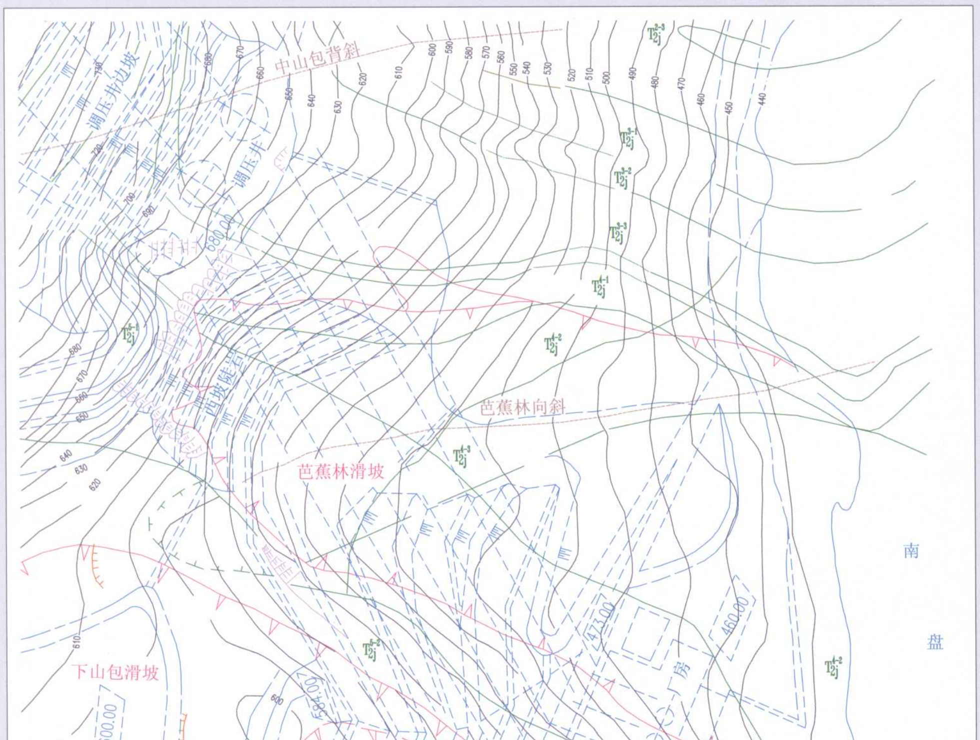

图1.4 厂区地质略图

Fig. 1.4 Geological map of the site

图1.5 正在施工中的厂房西坡

Fig. 1.5 The west slope of the plant under construction

1.2.1 West Slope

Located to the west of the plant, West Slope is a rock slope up to 164 m high measured from the bottom of the foundation pit to the crest. It is composed of two slopes: a 124 m high permanent slope and a 40 m high temporary slope. The slope strata are slightly inclined and are mainly composed of Jiangdonggou group $T_{2j}^{4-1} \sim T_{2j}^{5-2}$ sandstone mixed with shale, and a thin layer of limestone. Due to the cutting of originally structured faults, a cracked-layer rock mass has been formed (Fig. 1.5).

During the excavation of the West Slope, the original positions of blast holes were displaced to various extents. However, this phenomenon disappeared once the rebalancing of gravity stress distribution due to excavation was over.

1.2.2 South Slope

The South Slope refers to the slope adjacent to the south end of the plant. Measured from the bottom of the foundation pit, the slope reaches 70 m high: the permanent slope is 30 m high while the temporary slope is 40 m high. The slope is composed of Jiangdonggou group T_{2j}^{5} sandstone with a thin shale interlayer, which dips inverse to the slope at an angle of around 60º. In general, slope ratios varied between 1：0.8 and 1：0.5 after excavation. Within a period of just over four months, there were three occurrences of slope toppling (Fig. 1.6).

After the toppling failures in the South Slope, measures were taken to enhance safety, namely excavating all the toppled rock mass, readjusting excavation slope ratios, and implementing protection measures for the excavated slopes such as grouting and anchoring, drainage, and reinforced concrete retaining walls with steel-bars for the root section.