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Geohazards and their control in the resettlement sites of the Three Gorges Project, Yangtze River, China

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ABSTRACT

The population to be resettled from the Three Gorges Reservoir of the Yangtze River is about 1.2 million. During the first period of the Project from 1993 to 1997, about 82 thousand people were resettled; whereas about 550 thousand will be resettled during the second period of the Project from 1997 to 2003, and over 600 thousand will be resettled during the third period of the Project by 2009. Resettlement is a great challenge, since in the vicinity of the reservoir, there is not much land suitable for constructing buildings and the area is subject to various geological hazards. The paper discusses the engineering geology of the area, especially the geological hazards and their control for resettlement. The control measures for major geological hazards that have a possibility of disrupting the navigation through the Yangtze River (such as the Lianziya hazardous rock mass, the Huanglashi Landslide, and Jiguanling Rockfall) are discussed in this paper. The geological hazard prevention projects undertaken for the resettlement in the new sites (such as Waxian, Wushan, and Badong) is also described.

INTRODUCTION

The Yangtze River was successfully dammed in November 1997 by the Three Gorges Project (Plate 1), and it was also the symbolic end of the first period of resettlement. As the planned normal reservoir water level is at an elevation of 175 m, the submerged zone occupies 17 cities and 114 towns covering about 630 km^2, from where about 1.2 million of population has to be resettled. During the first period of the project (from 1993 to 1997), 82 thousand people were resettled, whereas 550 thousand will be resettled during the second period (from 1997 to 2003), and over 600 thousand of them will be shifted during the third period by 2009. Therefore, the last two periods of resettlement are more complicated and vital.

An extensive geological survey has been carried out for decades and it has provided a very good geological input to relocation planning. As resettlement is underway, new geological problems are emerging. Most of the new cities (out of them, 13 are the major ones) are suffering from the geohazards (Fig. 1). According to the investigation, over

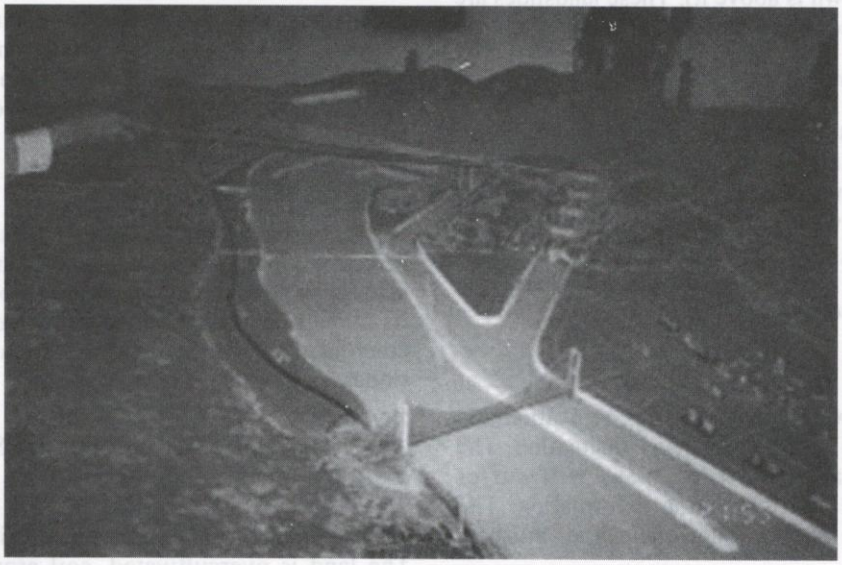

Plate 1: Layout of the Three Gorges Dam

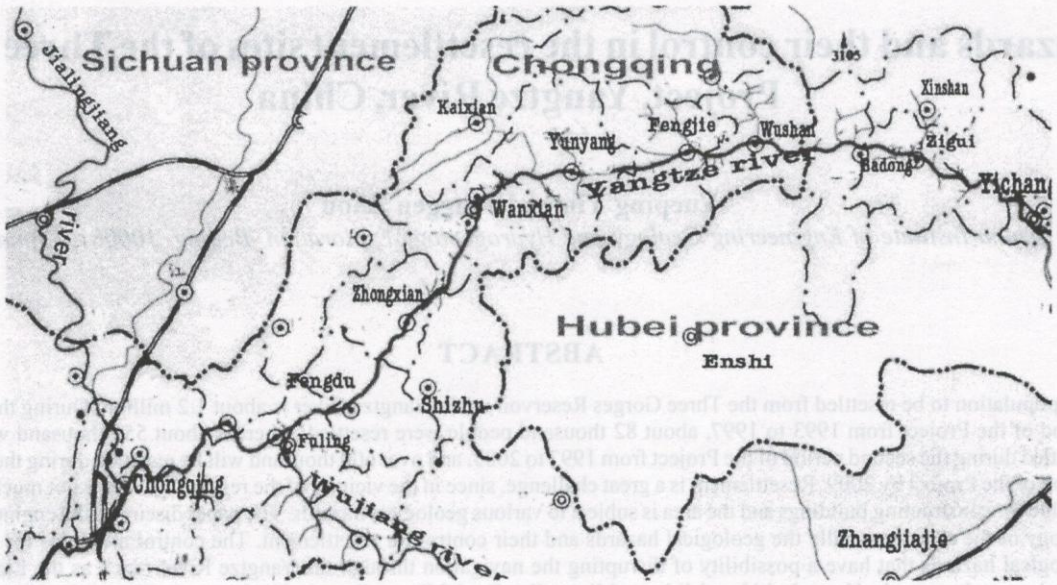

Fig. 1: Location of the main resettlement sites (cities) in the reservoir area of the Three Gorges Project

1500 landslides, rockfalls, and mudflows are present in the resettlement areas, and their mitigation is urgently needed.

GEOHAZARDS DUE TO RESETTLEMENT AND RESERVOIR STORAGE

Landslide and rockfall

The shoreline length of the main river course and its tributaries is 5,014 km, of which, the main course occupies 1,334 km. There are more than 400 landslides along the 175 m elevation line (i.e., their toe lies below the reservoir normal water level and the crown is above it). These landslides are the most dangerous ones since their toe is submerged.

Mudflow and debris flows

As the land for resettlement is not enough, some part flatland of floodplain and waste material fill are used as the relocation sites, and they may cause severe mudflow due to the improper waste material disposal and poor drainage. For example, Xingshan, Zigui, Badong, Wushan, Fengjie, and other new cities suffered from the hazards last year during the rainy season.

Karst hazard

Many karst caves were detected during relocation and they may collapse due to the water level fluctuation. The karst breccia and karstified rock mass will suffer from the slope failure and foundation deformation. The karst hazard is high in the new sites of Fengjie, Wushan, and Badong.

Shore slope instability

The reservoir water level will rise by 100 m (from 70 to 175 m) and will fluctuate by 30 m (between 145 and 175 m) annually. Consequently, the shore slope will be severely affected. In the reservoir region, 37 segments of the shoreline (72 km or 1.5% of total length) are highly unstable, and 102 segments (281 km or 5.6% of the total length) are moderately unstable.

Reservoir-induced earthquake

The reservoir-induced earthquakes are the potential threat to resettlement sites. According to the authentic predictions, the magnitude of the earthquake in the dam region is 4.0 Ms, it is 5.0–5.5 between Xiangxi and Beishi, and less than 4.0 in the Carbonate Formation region, whereas the intensity of earthquake in these areas varies from VI to VII.

Ecological hazards

The best terraces (i.e. No. 1 and 2) suitable for settlement lie below 175 m, and hence will be submerged. The strip of land above it (which is at an elevation over 200 m) is narrow. Its climate is harsh and the vegetation is sparse. On the other hand, many new building sites are located on the cut slopes of trenches.

GEOHAZARDS IN THE RESETTLEMENT AREAS

The vicinity of the reservoir area is densely populated. The land is overcultivated, soil erosion is severe, land

resources are scarce, and geo-environment is degraded. The problems related to these factors are described below.

Complex geological conditions

The region lies in the complex zone of three geological structures. Most of the flatland will be submerged, and a considerable portion of the remaining flatland is made up of the Quaternary landslide and rockfall deposits. For the purpose of limiting the adverse environmental impacts, the best way of resettlement would have been to move out of the Three Gorges zone, but it is not possible owing to social and cultural reasons. The site selection does not depend only on good geological conditions, and a number of sites had to be located on the landslide zones for the aforementioned reasons.

Stage of geological survey

The earlier study on the geo-environment was conducted in mid 1980s following the previous high water level of 150 m, and it had recommended 13 city sites for resettlement. Since 1992, a more detailed geological survey has been undertaken for new sites of 13 major cities and 163 towns. It will provide a scientific basis in resettlement planning.

The construction is validating the significance of the geological survey. However, owing to the lack of geological information in the new areas, the data of planning stage are being extrapolated to the preliminary design, and even detailed design and construction. This is done, as the construction in resettlement areas must follow the schedule of dam building.

Limitations of geological cognition

Hitherto nonexistent theories and methodologies were applied in the mitigation of geohazards in the Three Gorges Project, where the hazardous areas are located up to 100 m below water and the water level fluctuates by about 30 m annually. The treatments of geological problems are very careful, and understanding of the geology is getting further. For example, at the early stage of the resettlement, "large-scale excavation and large-scale filling" was avoided for the dam construction and preparation of resettlement sites. The recent practices show that the scientific methods applied were able to keep the project area stable and the resettlement sites environmentally and economically viable.

Durability of geological problems

The change in geo-environment by immense human activity within the next decade will be stronger than the natural geological processes operating there in 10, 100, or even 1000 years, and these activities may imbalance the slopes and trigger numerous geohazards.

The occurrence of geological hazards in the Three Gorges Reservoir can be divided into the following three periods:

a. during the first period (before 1993), when the dam construction began, there were mainly natural geological hazards with some caused by human activity (i.e. the Jipazi landslide, the Xintan landslide, and the Badong mudflow);
b. during the second period (from 1993 to 2003), geological hazards are related mainly to toe-cutting of slopes and waste material disposal (i.e. the Badong Erdaogou landslide and the Waxian Douyapeng landslide); and
c. during the third period (after 2003, especially, from 2003 to 2009), geological hazards will be caused by the water level fluctuations and the resettlement of more than 600 thousand people.

EXAMPLES OF MAJOR GEOHAZARD CONTROLS

Lots of controlling and monitoring on major geohazards have been completed in the reservoir area. They successfully mitigate the disasters. Especially, in the rainy season of 1998, no one was injured by hundreds of geohazards in resettlement areas because of the timely warning system.

Hazardous rock mass of Lianziya

The hazardous rock mass of Lianziya is situated on the southern bank of the Yangtze River in the Zigui County of the Hubei Province. It is facing the Xintan landslide across the Yangtze River, 27 km away from the Three Gorges Dam site. It is an elongated cracked rock mass running from north to south, and is 700 m long, 30 to 180 m wide, and over 100 m high. It is narrow and low in the south, and broad and high in the north. The unstable rock mass is intersected by more than 30 wide and huge fissures. The fissures are 60–170 m long, 0.5–5.0 m wide, and 50–150 m deep (Yin et al. 1996). The rock mass can be divided into the three segments of 800, 20, and 250 cubic metres from south to north, respectively.

The slope failures have occurred since last 500 years, and the most severe one had stopped the navigation through the river for 82 years. It can cause a disaster if the hazardous rock mass falls into the Yangtze River. A Steering Committee on the Lianziya and the Huanglashi (another huge dangerous landslide on the northern bank of the river) Geohazard Prevention was established in 1989, and it carried out the feasibility study for controlling the hazards. The implementation of control measures began in 1992 and was completed in 1998. The measures could successfully avoid the disasters related to heavy rainfall and high water level in 1998.

The hazardous rock mass consists of Permian limestone intercalated with several carbonaceous shale and marl layers, underlain by weak and already excavated coal beds. The

strata strike N30°–50°E and dip NW at angles varying from 27° to 35°. The hazardous rock mass was formed due to toppling of the cliff and the overhang formed by coal mining (the hollow area covers about 120,000 square metres and its height varies from 1.6 to 4.0 m) as well as due to karstification, weathering, and the presence of fissures and faults.

The geotechnical measures applied to control the rock mass included the installation of pre-stressed cable anchors, use of reinforced concrete filling, and the construction of surface drains and a protective dam. Nevertheless, the pre-stressed anchors played the most important role in stabilising the Lianziya hazardous rock mass. According to the detailed design standards, an anchoring force of 310,000 kN was needed with the anchoring grade of 1.1 million kN/m for the average depth of 35 m. Since the anchoring was carried out at a high cliff, three types of cable with strengths of 3,000 kN, 2,000 kN, and 1,000 kN, respectively were applied. The first type (about 50 cables) was used up to an elevation of 140 m (total anchoring force of 150,000 kN), the second type (about 50 cables) was applied mainly between 140 and 160 m (total anchoring force of 100,000 kN), and the third type (about 73 cables) was applied in the areas above 160 m (total anchoring force of 73,000 kN). The longest cable used for anchoring was of 62.5 m.

Huanglashi landslide area

The Huanglashi landslide area is located on the northern bank of the Yangtze River, 1.5 km east of the Badong County. It is a group of landslides that developed on a scarp slope of sandstone, mudstone, and marl, with a total volume of 40 million cubic metres and main body of 18 million cubic metres. The landslide has a long history of sliding, seriously threatens the navigation, and the slide-induced surge is inferred over 50 m, which may destroy the eastern part of the Badong County. Rainfall is the main triggering factor (Guo 1991). According to the monitoring data and test results, the landslide will be stable if the groundwater level is less than 0.2–0.4H (H being the depth of sliding). Hence, drainage was the principal prevention measure. About 6,763 m of surface drains were constructed during the first period of work and they proved to be an effective way of decreasing the groundwater level. Since the groundwater was also related to subsurface flow, the underground drainage tunnels were driven during the second period of work. These measures assured the stability of the Huanglashi landslide area.

Geological hazard prevention in the Waxian City

The Waxian City (also known as "the gateway to Sichuan") lies in a high landslide hazard zone of China. There are five huge landslides in the city, namely the Anlesi Landslide (1.1 km^2, 24.68 million cubic metres), Caojiezi Landslide (0.4 km^2, 6.96 million cubic metres), Yuhuangguan Landslide (1.96 km^2, 48.87 million cubic metres), Taibaiya Landslide (1.17 km^2, 4.65 million cubic metres), and Diaoyaping Landslide (0.47 km^2, 11.75 million cubic metres). They occupy an area sufficient for resettling 70 thousand people. At present, some of the landslides are very active and have destroyed the stabilisation measures. With the construction of the Three Gorges Reservoir, their toes will be submerged and the stability will decrease further. It is vital to control the landslide movement for ensuring the safety of construction. Since 1990, some landslides have been controlled successfully (such as the Douyapeng Landslide and Wangjianglu Landslide, located on the Taibaiya Landslide front) and the others are being stabilised.

Geological hazard prevention in the Badong County

The Badong County, located on the southern bank of the Yangtze River, was the first one used for the resettlement, but during the construction in 1980s, a large ancient landslide was discovered, and some buildings were damaged. In June 1995, the Erdaogou Landslide started moving and threatened the safety of new buildings and the highway. Various prevention measures (including piles, pre-stressed anchors, and surface drains) were undertaken to control the slide and ensure the stability of buildings. In October 1995, the Sandaogou Landslide moved into the Yangtze River, and affected the navigation. Since the geological hazards are very severe, the resettlement sites are relocated several times, and now, a relatively stable site has been found.

Geological hazard prevention in the Wushan County

In the new site of Wushan County, landslide hazards are quite severe. There exist five huge landslides in the county, namely the Dengjiawuchang Landslide (0.17 km^2, 5.18 million m^3), Yuhuangge Landslide (0.03 km^2, 1.07 million m^3), Baimenpo Landslide (0.04 km^2, 1.05 million m^3), Yanchanghou Landslide (0.05 km^2, 1.01 million m^3), and Xiufengsi Landslide (0.13 km^2, 4.84 million m^3). The total area of landslide is equal to the area for resettlement of 7.1 thousand people. Besides, in the new site, there is about 6 km^2 of avalanche deposit zone, and the shore collapse is severe. In fact, Wushan lies in the most severe geological hazard zone of the Three Gorges Reservoir area. An integrated programme will be undertaken in this area to combine landslide control, utilisation of ancient avalanche deposits, and prevention of shoreline erosion.

GEOHAZARD PREVENTION IN THE RESETTLEMENT AREAS

The following activities are planned for controlling the geohazards in the resettlement sites of the Three Gorges Project.

Formulating and implementing the geohazard prevention programme

Over 1,500 geohazard sites must be systematically surveyed and assessed for controlling the hazard. Special

attention will be paid to the geohazard investigation in rural areas. During the rainy season of 1998, the successful forecasting of mass movements saved the life of hundreds of people. It is also a good example of monitoring, prevention, and control.

Establishing the monitoring system

The deformation and evolution processes of mass movements are little understood, especially after the impounding of the reservoir. For this purpose, a good monitoring network will be established in the Three Gorges Reservoir area, and the dangers will be monitored regularly, especially during the rainy season, to safely evacuate the people and apply prompt mitigation measures in the hazardous areas.

Further investigations in rural areas

Since 1986, the detailed geological survey of the resettlement sites for cities and major hazard-prone areas has been conducted. But the survey in rural areas is lagging behind. This is an important factor affecting the success of the Three Gorges Project. There are about 618 major resettled spots in the rural areas, covering 352 thousand people. It is proposed to carry out the geohazard survey, monitoring, and prevention in 113 resettled towns and 618 major rural spots.

Geo-environmental effects of slope cutting and waste material disposal

Because of the Three Gorges Project, there is a great opportunity for urbanisation and economic growth in the vicinity of the reservoir. But, high cut slopes and sites of enormous waste material disposal are the obstacles. In these areas, an unsound drainage system may trigger off slope instabilities. Therefore, it is proposed to carry out a systematic investigation of cut slopes and waste material disposal sites, and to provide appropriate control measures.

Geo-environmental impact on steep slopes

In the Three Gorges Project area, the flatland is 4.7%, the rolling hills occupy 16.5%, and the mountainous area is 78.8%. The No. 1 and 2 terraces (most suitable for living) will be submerged in the reservoir, and the remaining land is not suitable for resettlement. Discriminate felling and haphazard cultivation are the two main sources of human-induced soil erosion. They are becoming a new source of environmental pollution in the Yangtze River.

To conduct comprehensive shore slope protection and development

The stability of shore slope is a crucial problem in the new sites. Over 400 landslides are across the 175 m water level line where large-scale slides may occur due to impounding. They may cause a severe hazard to the resettlement sites. A special survey of shoreline will be carried out, and a comprehensive programme on shore slope protection and development will be formulated. It will include landslide control, waste material disposal, and land accretion as well as population resettlement, road construction, and harbour building.

Application of new technology

There are many success stories and lessons learnt from failures while carrying out the resettlement in such areas as Badong, Waxian, and other cities. Meanwhile, many new technologies, methods, and theories, such as geo-engineering method, pre-stressing, and bioengineering were also applied.

Improving the administrative system

The administration of geological hazards needs to be strengthened, especially in preventing the natural hazards and avoiding the man-induced geohazard in resettlement areas (Zhou 1999). Firstly, the knowledge of geological hazard and control must be popularised in the public. Secondly, the duty and fund source should be specified for the prevention and control of geological hazards. Thirdly, standardisation is needed; the prevention and control of specific geological hazards need to work out a complete standard from survey, design, construction, and monitoring. Fourthly, special regulations and bylaws are necessary for prevention and control of geological hazards.

CONCLUSIONS

The Three Gorges Project area lies in one of the most severe geological hazard zones. The resettled population of the Three Gorges Reservoir of the Yangtze River is about 1.2 million. The occurrence of geological hazards in the Three Gorges Reservoir can be divided into the following three periods: a. during the first period (before 1993), when the dam construction began, there were mainly natural geological hazards with some caused by human activity; b. during the second period (from 1993 to 2003), geological hazards are related mainly to toe cutting of slopes and waste material disposal; and c. during the third period (after 2003, especially, from 2003 to 2009), geological hazards will be caused by the water level fluctuations. Many problems related to protection, remedy, and utilisation of landslide and rockfall deposits as well as management of "large-scale excavation and large-scale filling" for the construction and relocation will be encountered in the third period. Geological hazards will be more frequent and severe after impounding the reservoir.

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