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Geohazards in the three Gorges Reservoir Area, China – Lessons learned from decades of research

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ABSTRACT

The impoundment of the 660-km long reservoir behind the huge Three Gorges Dam, the world's largest hydropower station, increased regional seismicity and reactivated severe geohazards. Before the reservoir filling was initiated in 2003, the region had approximately two earthquakes per year with magnitudes between 3.0 and 4.9; after the full impoundment in 2008, approximately 14 earthquakes per year occurred with magnitudes between 3.0 and 5.4. In addition, hundreds of landslides were reactivated and are now in a state of intermittent creep. Many landslides exhibit step-like annual pattern of displacement in response to quasi-regular variations in seasonal rainfall and reservoir level. Additional problems include rock avalanches, impulse waves and debris flows. The seriousness of these events motivated numerous studies that resulted in 1) Better insight into the behavior and evolution mechanism of geohazards in the Three Gorges Reservoir Area (TGRA); 2) Implementation of monitoring and early-warning systems of geohazards; and 3) Design and construction of preventive countermeasures including lattice anchors, stabilizing piles, rock bolts, drainage canals and tunnels, and huge revetments. This paper reviews the hydro-geologic setting of TGRA geohazards, examines their occurrence and evolution in the past few decades, offers insight learned from extensive research on TGRA geohazards, and suggests topics for future research to address the remaining challenges.

1. Introduction

The Three Gorges Dam on the Yangtze River has the largest installed hydropower capacity in the world, and the impoundment of the massive Three Gorges Reservoir (hereinafter referred to as TGR) that began in 2003 required the relocation of 1.2 million people (Yin et al., 2016). Water levels subsequently rose as much as 107 m over the impounded ground, creating a 660 km-long backwater area (Wang et al., 2014) exposed to geohazards. Even prior to the impoundment, an average of approximately five major geohazard events per year had occurred in this area. These geohazards were mostly in the form of landslides and rock avalanches, but debris flows, ground fissures, ground subsidence, karst collapses and earthquakes had also been reported (Wang and Li, 2009).

The reservoir impoundment has clearly increased the frequency of geohazard events in mountainous, tectonically active TGR area. Most significant was the reactivation of large landslides, whose newly submerged toes became subject to fluctuating hydrologic conditions (Song et al., 2018). An extreme case was the fatal Qianjiangping landslide and its associated, 30-m high impulse wave, which occurred shortly after the initial TGR impoundment, causing 24 deaths, destroying 346 houses, and capsizing many ships (Jian et al., 2014; Tang et al., 2017). The resettlement program for the relocated people required many new development projects and constructions in TGRA, and the associated excavations, road building and side casting produced many oversteepened, potentially unstable slopes. Moreover, many faults, karst caves and mining chambers exist in TGRA, and they can be affected by the pressure of the impounded water. As a side effect, the frequency and magnitude of earthquakes has clearly increased in the TGRA, similarly to what had been observed in other cases of induced seismicity following large reservoir filling (Simpson et al., 1988).

A great deal of scientific research has been undertaken to identify and mitigate TGRA geohazards, starting from the planning phase of this huge construction (Three Gorges Dam) project and continuing until the present time. More than 4,000 articles have been published on various aspects of TGRA geohazards. These articles focused mainly on 1) Characterizing TGRA geohazards; 2) Evaluating how they evolved and behaved; 3) Designing, testing and installing preventive stabilization

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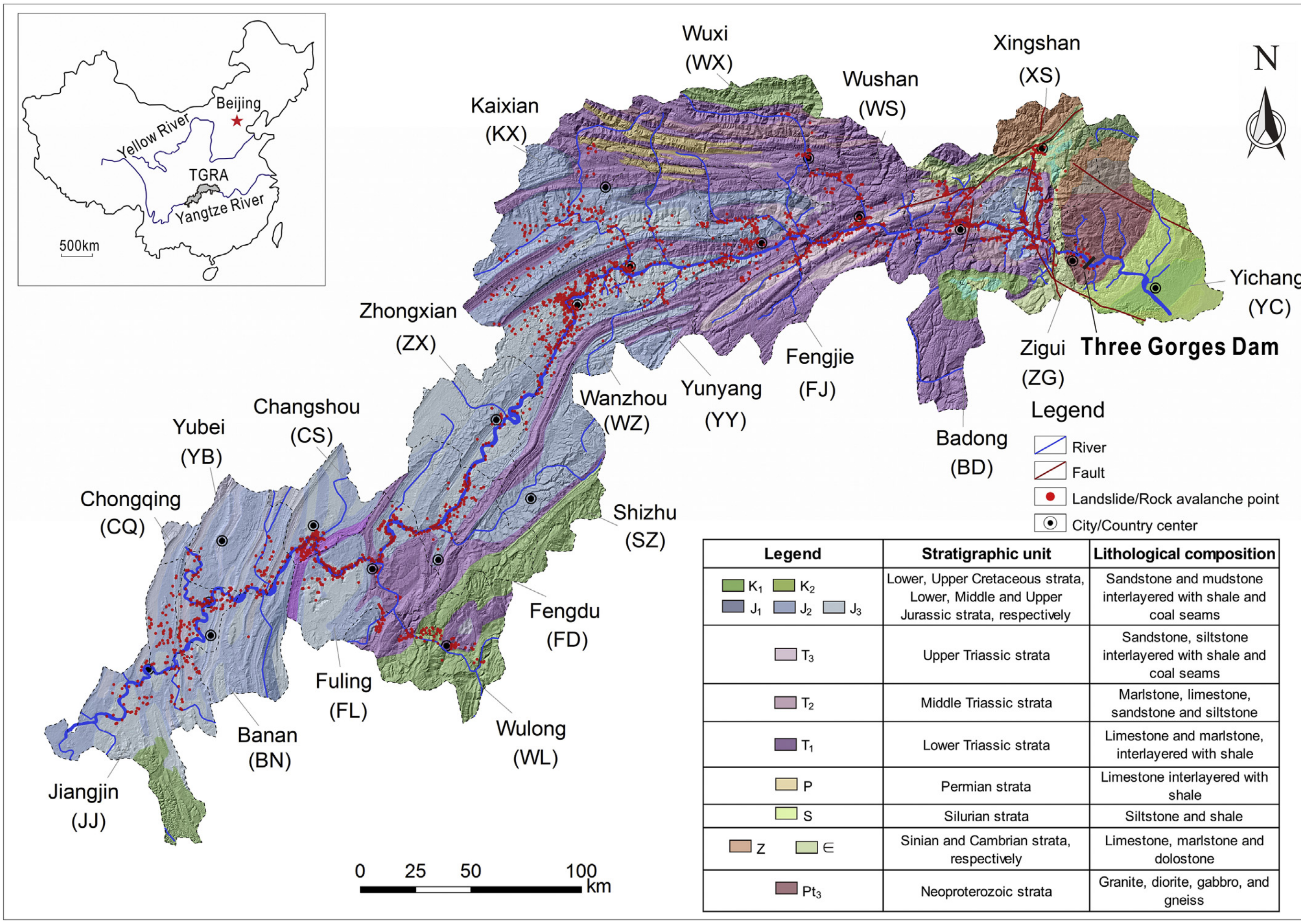

Fig. 1. Geological map of TGRA showing the locations of landslides and rock avalanches (red dots). The impounded area extends from the dam site in the east to Jiangjin in the west and mainly includes landslide-prone Triassic and Jurassic units. Geologic base map from http://geocloud.cgs.gov.cn (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

measures, and 4) Monitoring geohazards and implementing early warning protocols to prevent potential catastrophic events. This paper attempts to summarize the massive corpora of research work, with the goal of gaining insights toward effective prevention and mitigation of TGRA geohazards. The paper also discusses challenges facing the engineering geologists in the prevention and mitigation of TGRA geohazards and offers suggestions for further research toward the goal of disaster reduction.

2. Geological setting and geohazards in TGRA

2.1. Geological and environmental background of TGRA

TGRA includes the regions of Yichang, Zigui, Xingshan, Badong, Wushan, Wuxi, Fengjie, Yunyang, Wanzhou, Kaixian, Zhongxian, Shizhu, Fengdu, Changshou, Fuling, Wulong, Yubei, Banan, Chongqing and Jiangjin (Fig. 1). The total lengths of the banks of the mainstream (the Yangtze River) and its tributaries are about 660 km and 1840 km, respectively.

The landscape of TGRA was shaped by major tectonic events. Yanshan orogeny in the Late Jurassic formed the terrain skeleton of mountains. Following the Himalayan orogeny in the Neogene, long-term erosional processes gradually transformed the area into the present-day landscape with moderate- to low-altitude mountains and river valleys. The section from Fengjie to the west of Zigui is topographically the highest, creating the famous Three Gorges (Qutang Gorge, Wu Gorge, and Xiling Gorge). The elevation declines westwards and eastwards from the highest part, forming hilly landscape and moderate-altitude mountains, respectively. The trend of the mountains is controlled by major geological structures.

The age of the geological units varies from the pre-Sinian to the Quaternary. There are no units of the Upper Silurian, Lower Devonian, and Upper Carboniferous age. The so-called red strata are widespread in TGRA, accounting for approximately 72% of the total length of the TGR banks. Here, the red strata refer to sandstone, mudstone, and sandstone interbedded with mudstone layers. The red strata were deposited in the Jurassic and Triassic periods. The red strata of Jurassic age are predominant in TGRA, mainly exposed in the west of Fengjie and eastern Zigui (Fig. 1). The Triassic age red strata appear only in some parts of Badong and Zigui regions (Badong Formation). In addition to the red strata, other sedimentary rocks (limestone, marlstone, and dolostone) are also present in the area between Fengjie and Zigui. These hard rocks form the steep gorges and valleys in the Fengjie-Zigui area. Metamorphic complexes and magmatic rocks crop out in a relatively small area near the dam site.

The main geological structure of TGRA is a prominent fold belt, which reflects the influence of multiple tectonic events. Starting from the west part of TGRA, the fold belt changes its trend from north-south to east-west direction and joins the Zigui syncline in the east. Ample evidence of intensive tectonics is observed in the area east of Fengjie, which includes large-scale structures such as the Huangling anticline, Zigui syncline, Guandukou syncline, Xiannvshan fault, Jiuwanxi fault

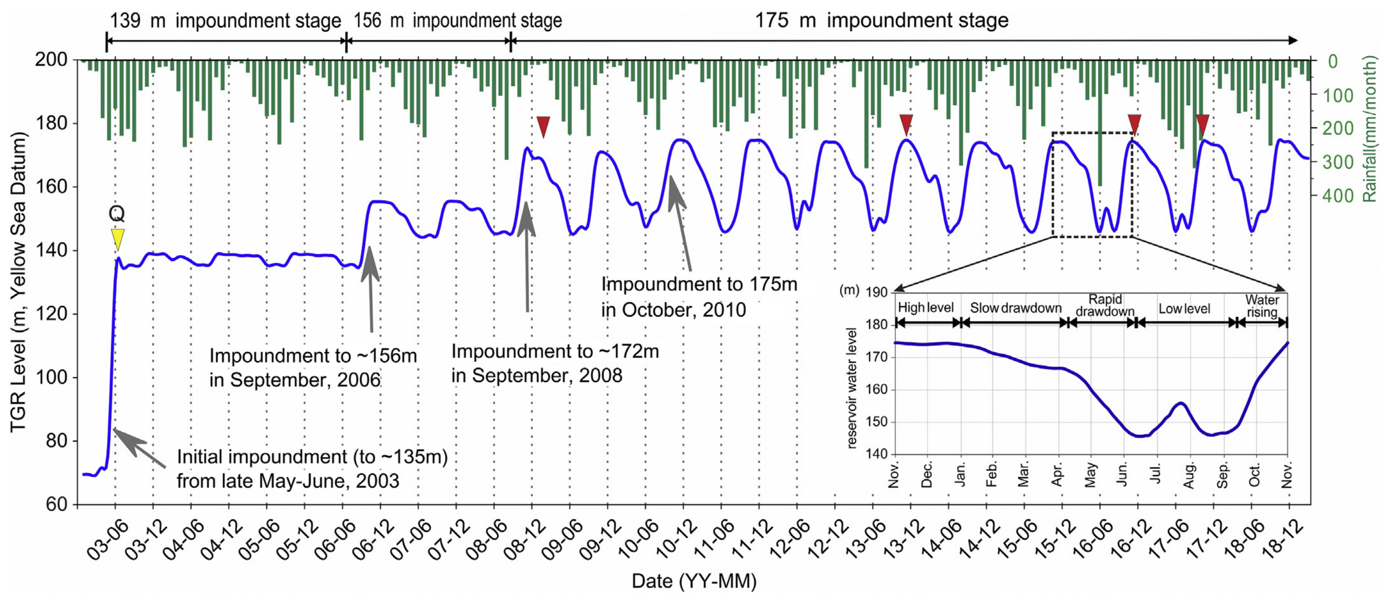

Fig. 2. Water level variation in the Three Gorges Reservoir. Impoundment began in 2003 and since 2008 water level has been adjusted annually to maintain a flood control level between 145 m and 175 m. Rainfall data are from the Wanzhou district located in the middle of the TGRA. The inverted yellow triangle marks the occurrence of the huge Qianjiangping (Q) landslide in 2003, and the four inverted red triangles represent earthquakes with magnitudes above 5.0. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and Tianyangping fault.

The TGRA is in the middle part of China and has a wet subtropical climate; it is warm and humid with abundant rainfall. Monsoon leads to a notable variation of heat from city to city during the year, while the rainfall is mainly concentrated in summer. The largest precipitation is in Wanzhou, with about 1930 mm annually (He et al., 2008). Moving away from Wanzhou to either part (east or west), the precipitation shows a decreasing trend. The smallest precipitation (about 996 mm annually) is in Zigui (Fig. 1).

Since the impoundment, the water level of the TGR progressed through three stages (Fig. 2). The first stage was the trial reservoir impoundment from April 2003 to September 2006 when the water level was raised from 69 m to 139 m ASL (above sea level) within the first two months, and then varied slightly. The second stage was from September 2006 to September 2008, when the water level was raised from 139 m to 156 m ASL in one month, and subsequently varied annually between 145 m and 156 m ASL. The third stage began when the maximal water level of the reservoir was raised to 172 m ASL in 2008, keeping the fluctuation between 145 m and 172 m ASL from 2008 to 2010. Thereafter the water level is managed to fluctuate annually between 145 m and 175 m ASL. During the fluctuation process, the water level goes through a sequence of stages, including slow drawdown, rapid drawdown, low level, water rising and high level.

2.2. Characteristics of TGRA geohazards

Landslides, rock avalanches, debris flows, ground fissures, and ground subsidence are the main instability phenomena in TGRA. There are 4429 geological hazards in TGRA from Yichang to Jiangjin along the Yangtze River. Among them, 4256 are landslides and rock avalanches with a total volume of about 4.24 billion m^3, and the rest includes 58 debris flows, 42 ground fissures and 73 cases of ground subsidence.

2.3. Characteristics of landslide and rock avalanche hazards

The characteristics of landslide and rock avalanche hazards in TGRA can be summarized as follows:

(1) Spatial distribution

Geohazards tend to concentrate along the Yangtze River and some of its tributaries but are most common to the east of Wanzhou (Fig. 1). Landslides and rock avalanches are particularly abundant in Zigui and Badong counties (Fig. 3). Considering the tributary rivers, the geohazards are most frequent in the catchments of Xiangxi, Guizhou, Qinggan, Caotang, Meixi, and Wujiang rivers, accounting for 44.3% of the total number of landslides and rock avalanches and 63.4% of the total volume of the geohazards present along the Yangtze River tributaries.

(2) Slide-prone strata

Lithology is a major factor controlling the distribution of TGRA geohazards (Li et al., 2018). The sandstone, mudstone, and sandstone interbedded with mudstone layers of the Triassic Badong Formation and the Jurassic strata are known as the most slide-prone strata, bearing numerous rock avalanches and landslides. The volume of the rock avalanches and landslides identified in these strata accounts for 87.3% and 91.1%, respectively, of the total volume of TGRA rock avalanches and landslides.

No large rock avalanches or landslides are associated with the Precambrian magmatic and metamorphic rocks, and only small bank slump occurred in the weathered materials near the dam. Moreover, slope instabilities are relatively infrequent in the carbonate rock area that hosts the famous Three Gorges. Less than 8% of the total volume of identified landslides and rock avalanches are associated with these rocks.

(3) Influence of geologic structure

The landslides in the TGRA are likely to occur where strata dip at moderate angles toward the rivers, particularly on the flanks of anticlines and cores of synclines. These settings are ideal for the development of large consequent bedding landslides. Two prominent examples of such TGRA landslides are the Qianjiangping and the Huangtupo landslides developed, respectively, in the Zigui and the Guandukou synclines.

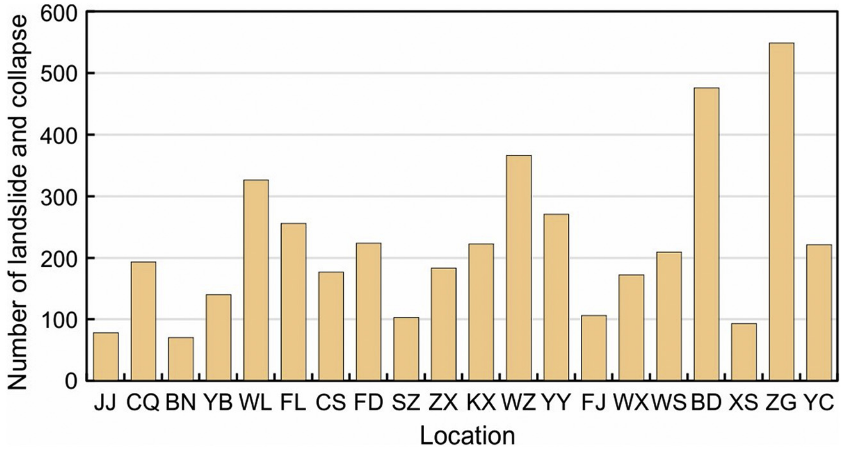

Fig. 3. Number of landslides and rock avalanches along the impounded reach of the Yangtze River starting from the westernmost area of Jiangjin (JJ) to the easternmost area of Yichang (YC). (See Fig. 1 for location.)

2.4. Characteristics of reservoir-induced earthquakes in TGRA

Seismic records from Hubei Institute of Seismology, China Earthquake Administration, show that 192 earthquakes with magnitude (M) ≥3.0 occurred in TGRA between 1995 and 2018 (Fig. 4). Among these, 170 earthquakes had magnitudes of 3.0 ≤ M < 3.9, while 18 had 4.0 ≤ M < 4.9 and four had M ≥ 5.0.

As illustrated in Fig. 4, the frequency and intensity of earthquakes were low before the first TGRA impoundment (2003). Based on the monitoring data from 1995 to 2001, the average number of $M \geq 3.0$ earthquakes per year was 2.4, except in 2001 (11 events). In those seven years, the magnitude of the largest earthquake was 4.4 (1997 event), and only three events had magnitude > 4.0.

Seismic activity did not change during the trial impoundment period (June 2003 to September 2006), when the water level first rose to 135 m ASL. Moreover, seismic activity increased only slightly during the second impoundment stage (September 2006 to September 2008), when the water level rose to 156 m ASL. However, seismic activity increased significantly following the final impoundment stage (after September 2008); approximately 14 events per year with M > 3.0 now appears to be a norm, compared to 2.4 events per year prior to the impoundment. In addition, four events with M ≥ 5.0 occurred in this stage, compared to none between 1995 and 2008. Clearly, both frequency and intensity of the earthquakes have risen since the full impoundment in September 2008.

3. Trends of research on TGRA Geohazards

3.1. Research and engineering work relevant to TGRA geohazards

TGRA is extremely important for the study of geological disasters. Several large-scale research projects were funded to examine the key scientific and technological issues for the prevention and control of geohazards in this area. Important research results were obtained, including those related to the triggering mechanism of geohazards, geotechnical properties of special lithologies, prevention and control methods, monitoring and large-scale field experimental stations. The major research and development activities and their outcomes are summarized as follows:

(1) In-situ investigation, multi-parameter monitoring, and physical model tests were conducted to study the behavior and evolution

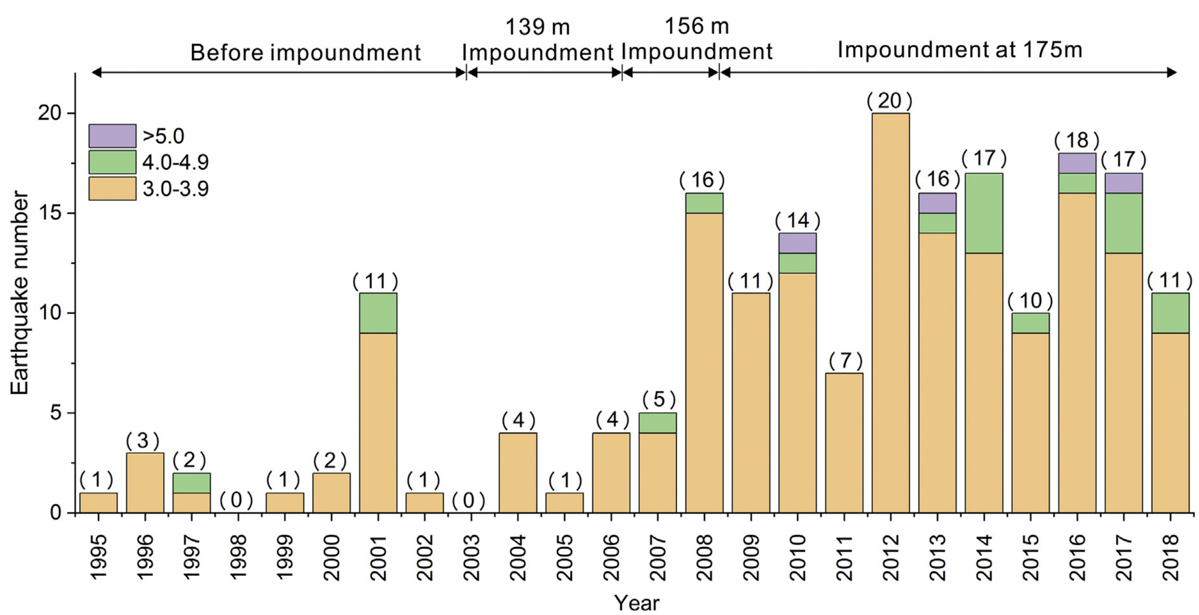

Fig. 4. Annual number of earthquake occurrences in the TGRA from 1995 to 2018. Only epicenters within the shaded area in the inset in Fig. 1 are included in the count. Seismic data are taken from Hubei Earthquake Monitoring Network, China Earthquake Administration.

process of TGRA geohazards. The established tempo-spatial evolution mechanisms and deformation-failure modes show how rainfall and reservoir water level fluctuations affect the geohazards (Tang et al., 2015a,b,c; Wang et al., 2016; Wu et al., 2019; Song et al., 2018). Prediction and evaluation models for landslide-driven impulse waves in the reservoir were also developed (Yin et al., 2012; Huang et al., 2012).

(2) The engineering geological properties of the slide-prone strata and the key areas of large landslides were examined. The degradation and disintegration processes under the effect of the reservoir water fluctuation were studied, focusing on the rock masses from the red strata of the Jurassic age and the Triassic Badong Formation (Jiao et al., 2014; Shen et al., 2019). The shear and rheology properties of the slip zones in large landslides were investigated through in-situ triaxial creep tests, which provided data for further analysis of TGRA landslides (Tan et al., 2018a,b,c).

(3) Different control methods, including deep drainage, anti-sliding piles and anchor cables were successfully applied to mitigate large TGRA geohazards. The successful mitigation projects, including those to stabilize the Lianziya unstable rock mass and the Hongshibao landslide, provided valuable experience for the prevention and control of geohazards in the area. Through these on-site demonstration projects, standards were established for the prevention and control of TGRA geohazards.

(4) A modern monitoring network of TGRA geohazards was constructed by combining systems of automatic monitoring, real-time information release and remote transmission. An early warning system was established based on the identification of the geohazard evolution stage (Xu et al., 2008). Many TGRA geohazards were successfully forecasted, such as the Xintan landslide, based on comprehensive monitoring and warning systems.

(5) Large-scale field experimental stations for the study and monitoring of TRGA geohazards were constructed. Among them was the Badong field experimental station (Tang et al., 2015a,b,c), which is the largest experimental facility ever built inside a landslide body. The Badong station was constructed to provide support to research, teaching, and risk communication of TGRA geohazards. The Badong experimental station has marked one of the most significant advances for the discipline of engineering geology in China.

3.2. *Trends of TGRA geohazards research based on scientific literature survey*

Numerous research results have been published in journals or other media to elucidate TGRA geohazards. A bibliometric analysis was applied to a large sample of relevant articles from Science Citation Index Expanded (SCIE) database and Chinese National Knowledge Infrastructure (CNKI) database. These two databases cover the vast majority of articles that are related to TGRA geohazards.

The time span of this survey was limited to the period of 1981–2019, since few articles were found before 1981 in the above databases. Before the search process, a series of terms related to the geohazards were selected. Publications were found by searching the term "three gorges" and one of following terms: "geohazard", "hazard", "landslide", "slope", "rockfall", "rock avalanche", "ground fissure", "earthquake", "debris flow", "impulse wave", "tsunami", "rock mechanics", "rockmass mechanics", "soil mechanics", "factor of safety" and "susceptibility" in the title, abstract or keywords of a paper. Eventually, 1002 publications and 2857 publications were identified in SCIE and CNKI respectively.

The statistics regarding the five most investigated types of geohazards, i.e., landslide, earthquake, impulse wave, rock avalanche and debris flow, are shown in Fig. 5. Landslide is the most frequently studied geohazard topic in the TGRA literature, followed by earthquake, impulse wave, rock avalanche and debris flow. Articles in English and in Chinese reveal the same trend.

The most frequently used keywords were obtained from an open-source search results clustering engine (CARROT[2]; https://project.carrot2.org/). Fig. 6 shows the results of this search, in which "Reservoir landslide" is the most frequently used keyword. Focusing on TGRA geohazards, the most mentioned terms in these articles include landslide monitoring, landslide stability, landslide deformation, landslide displacement and mechanism.

4. Assessment of TGRA Geohazards

4.1. *Assessment of reservoir landslides and their evolution mechanisms*

Evolution mechanism is an important aspect in the study of reservoir landslides. The dynamic characteristics of landslide evolution and the influencing factors have been widely investigated in TGRA-related studies.

4.1.1. *Dynamic characteristics of TGRA landslide evolution*

(1) Deformation process of landslides

Deformation and failure processes of reservoir landslides were studied via site survey, monitoring, physical model test and numerical simulation. Many TGRA landslides were affected by the periodic variations of water level and rainfall. Some landslides deformed intermittently and showed step-like cumulative displacement curves, such as the Baishuihe landslide (Li et al., 2010), Shuping landslide (Wu et al., 2019) and Outang landslide (Yin et al., 2016). Other TGRA landslides deformed continuously and had linear-like curves of cumulative displacement, such as the Majiagou landslide (Ma et al., 2017a,b).

Some investigators used physical model tests and numerical simulations to study and reconstruct the evolution process and deformation mechanism of landslides, while others used finite element methods to study the coupling effect of rainfall and reservoir water level variation (Jiang et al., 2011; Zhao et al., 2017). Rheology model was adopted to study the mechanism of the Anlesi landslide (Jian et al., 2009). Universal discrete code was applied to study the effects of rainfall and water level fluctuations on the behavior of the Quchi landslides (Huang et al., 2018).

(2) Mechanical characteristics of reservoir landslides

Based on the role of water in the deformation of reservoir landslides, TGRA landslides can be classified as seepage-induced or buoyancy-induced landslides. In the seepage-induced landslides deformation mainly occurs when the reservoir water declines (Fig. 7A), while in the buoyancy-induced landslides deformation mainly occurs when the reservoir water level is high (Fig. 7B). The seepage-induced landslides are more prone to form in low permeability sliding material. Porewater pressure is difficult to dissipate when the reservoir water level drops suddenly, and this produces outward seepage force that tends to destabilize the landslide. The two types of deformation behavior are illustrated by the Baishuihe landslide (Fig. 7C) and the Muyubao landslide (Fig. 7D).

In addition to the hydro-mechanical effects caused by the fluctuation of water level, the mechanical properties of slip zone were found to be a controlling factor in the deformation and failure process of landslides. Ring shear tests were conducted to investigate the residual strength of the slip zone of the Qianjiangping landslide (Wang et al., 2008). Rheology tests, including ring shear creep test (Wang et al., 2018) and triaxial creep test (Miao et al., 2014; Li et al., 2019a,b), were conducted to characterize the long-term strength and creep behavior. A large-scale in-situ triaxial creep test was carried out in the slip zone of the Huangtupo landslide at the Badong in-situ experimental station (Tan et al., 2018a,b,c). The weakening of the slip zone material was studied by wetting-dry cycling tests, simulating the condition of periodic water level fluctuation (Jiao et al., 2014).

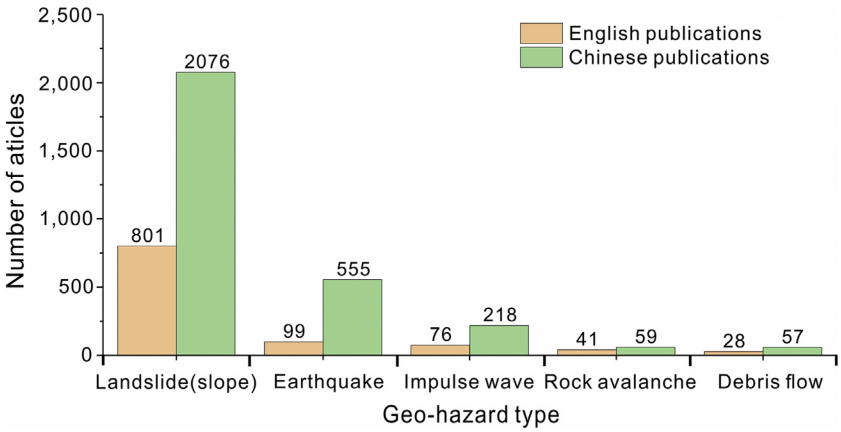

Fig. 5. Number of articles published since 1981 concerning various TGRA geohazards.

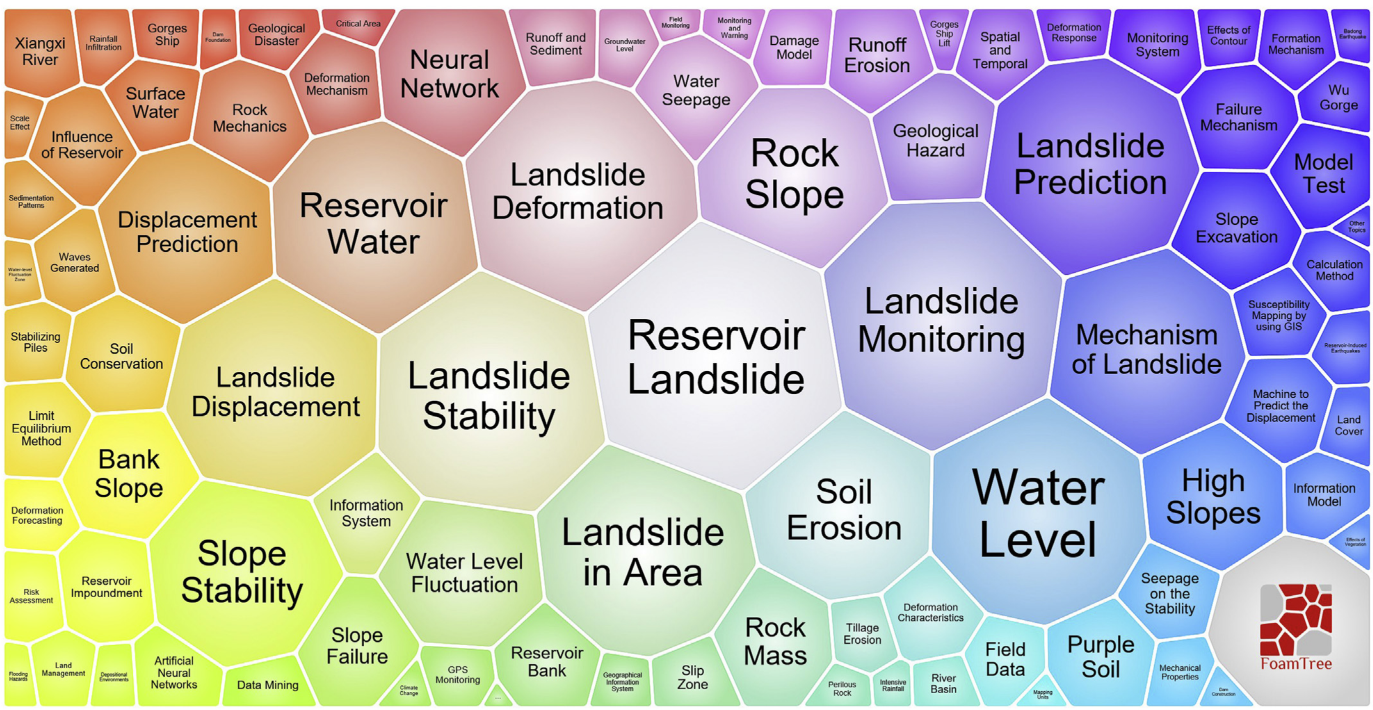

Fig. 6. Most "active" terms used in the articles related to TGRA geohazards.

4.1.2. Effect of rainfall and fluctuating water level on the evolution of TGRA landslides

(1) Effect of rainfall

Rainfall was found to be one of the most important causative factors of TGRA landslides. Different workers used field monitoring to investigate the water infiltration mechanism and effect of rainfall on slope stability. Observation wells were constructed in typical colluvial landslides (Tang et al., 2015a,b,c) and decomposed granite slope (Zhang et al., 2000). The rainfall infiltration process was studied using the monitoring data on suction and temporary pore pressure variations during the rainfall. Additionally, the influence of rainfall characteristics (amount, intensity, distribution pattern) on slope stability were studied (Yang et al., 2017; Liu et al., 2018).

(2) Effect of reservoir water level flunctuation

The periodic TGR water level fluctuation can alter the seepage field, the stress field and the material properties, resulting in the change of slope stability. Such findings were reported by Hu et al. (2012), Zhang et al. (2014a,b) and Zhao et al. (2017). The effect of rising and falling water level was also studied through model test or numerical simulation considering different rates of water level variation (e.g., Sun et al., 2017). Further, Liao et al. (2005) demonstrated that slope stability was closely related to the variation of the permeability coefficient of rocks.

(3) Combined effect of rainfall and water level fluctuation

In many cases, the evolution of reservoir landslides depends on the combined (coupled) effect of rainfall and water level fluctuation. Some conceptual models were established to calculate the phreatic line (Wu et al., 2009; Sun et al., 2016a,b). Numerical simulations were used to study the characteristics of seepage field based on saturated-unsaturated theory (Miao et al., 2018). Many TGRA landslides have been continuously monitored. Based on the monitoring data, the influence of rainfall and water level fluctuation on the landslide deformation was analyzed (Li et al., 2010; Tang et al., 2015a,b,c; Wang et al., 2017). In

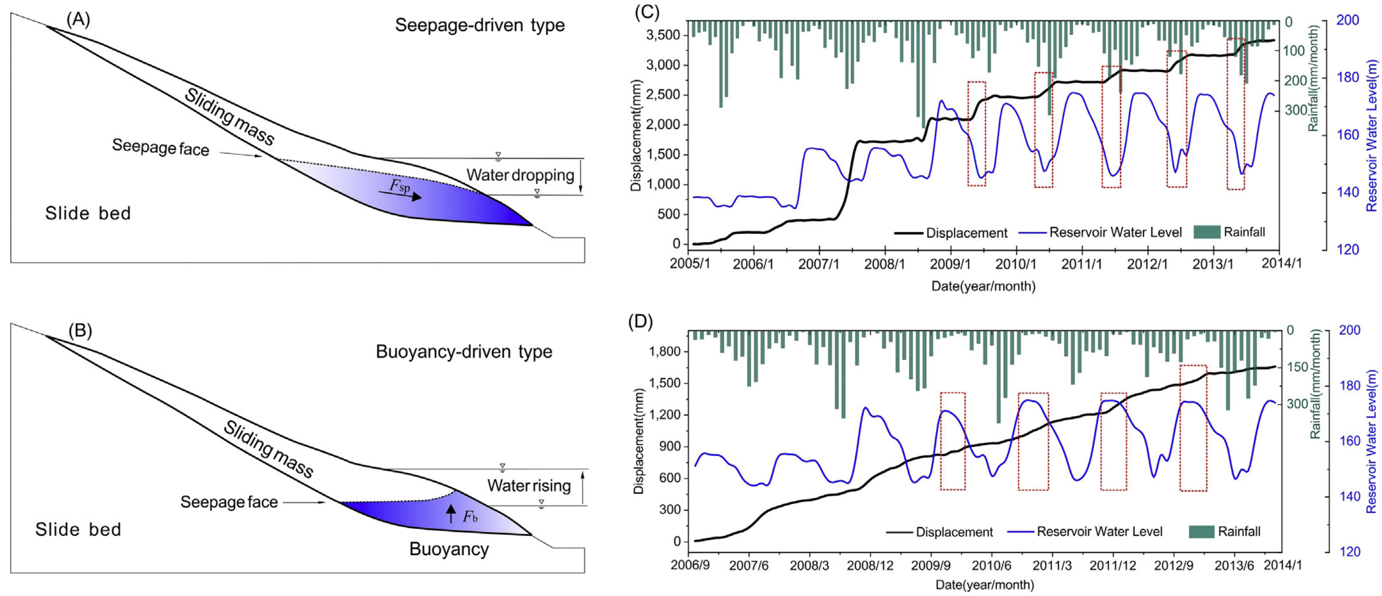

Fig. 7. Landslide deformation can accelerate by either rising or falling reservoir water level, depending on whether seepage forces (parts A, C) or buoyancy forces (parts B, D) are predominant. The differences between the seepage-driven Baishuihe landslide (C) and the buoyancy-driven Muyubao landslide (D) are observed through the corresponding periods of faster movement (red boxes). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

addition, data mining methods, such as grey relational grade analysis, two-step cluster analysis and Apriori algorithm analysis, were applied to examine and quantify the influence of rainfall and water level variation on landslide deformation (Ma et al., 2017a,b; Tan et al., 2018a,b,c).

4.1.3. Stability evaluation methods

The methods used in the evaluation of TGRA landslides transitioned from qualitative to quantitative approaches and from the deterministic to the probabilistic approaches.

(1) Qualitative methods

The qualitative methods, including engineering geological analogy, graphic method and expert system, are typically used in the early stage of landslide evaluation (Zhou, 1996; Zhu et al., 2014). Moreover, classification studies based on database management system (DBMS) and geological information system (GIS) were employed to evaluate the stability of slopes (Fourniadis et al., 2007).

(2) Limit equilibrium methods

The limit equilibrium methods applied in the stability evaluation of TGRA landslides include Swedish method, Janbu method, Bishop method, M-P method and Sarma method (Ma and Liang, 2002; Liu et al., 2007a,b). Some of these methods were further modified based on simplified boundary conditions and/or additional assumptions (Yong et al., 2016; Wang et al., 2017; Tang et al., 2017). Furthermore, the two-dimensional limited equilibrium method was extended to three-dimensional limited equilibrium method (Wang and Xu, 2013; Sun et al., 2016a,b).

(3) Numerical simulation methods

The strength reduction approach based on finite element method (FEM) was often adopted for the stability evaluation of TGRA landslides. The FEM-based strength reduction method was modified using the nonlinear strength reduction theory (Liu et al., 2007a,b). The two-dimensional strength reduction method was extended to the three-dimensional method (Deng et al., 2010). The interaction of seepage and stress fields based on the strength reduction method was further introduced for the stability analysis (Zhou et al., 2014). Additionally, the FEM-based strength reduction method was combined with the saturated-unsaturated theory to analyze the stability of the Bazimen landslide (Zhang and Cheng, 2011).

(4) Probabilistic analysis methods considering uncertainties

The geological model, mechanical properties and external factors that are required in the stability analysis of landslides can be complex and may not be characterized with certainty. Chai et al., 2007described the uncertainty of shear strength parameters of the slide zone in TGRA in the form of a probability distribution. Jiang et al. (2010) evaluated the instability (failure) probability of the Dagouwan landslide using the Monte Carlo simulation, which considers the uncertainty of the mechanical parameters. Li et al. (2014) studied the spatial variation of shear strength parameters and conducted reliability analysis of the Majiagou and Bazimen landslides.

4.1.4. Stability of the bank slopes during the TGR operation

The impoundment of the TGR changed the environmental conditions of the bank slopes and greatly affected their stability.

(1) Reservoir bank stability during the trial impoundment aimed at 135 m ASL

In the trial impoundment concluded in June 2003, the reservoir water level rose approximately 70 m to 135 m ASL without falling back. Monitoring showed that after this trial impoundment, 177 landslides occurred in TGRA during the period from 2003 to 2006. The movement of these landslides resulted in local cracking and destruction of houses, buildings and roadways, which affected 15,000 people and posed a threat to shipping in the Yangtze River. More than 6900 people were relocated during this impoundment. Among these landslides, the 15 million m^3 Qianjiangping landslide that occurred in July 2003 was the most significant. This landslide formed a dammed lake by blocking the Qinggan River, the first-order tributary of the Yangtze River. Thanks to the timely monitoring and early warning, 1200 residents were safely evacuated and permanently relocated afterwards.

(2) Reservoir bank stability during the impoundment aimed at 156 m ASL

During the period of the impoundment aimed at 156 m ASL, from September 2006 to September 2008, the water level fluctuated between 145 m ASL and 156 m ASL. A total of 152 landslides and significant deformations occurred in the whole reservoir area, resulting in the cracking of houses and roadways. About 3000 people were relocated during this impoundment period, and the emergency investigation, monitoring and rescue activities were carried out with approximately 180 emergency disposals in the reservoir area.

(3) Reservoir bank stability during the impoundment aimed at 175 m ASL

The impoundment aimed at 175 m ASL was carried out after the 2008 rainy season. Reservoir impoundment began on September 282,008 and was suspended on October 8, when the water level reached 156 m ASL. Then the reservoir impoundment restarted on October 17, 2008 and the water level reached 172 m ASL on November 14. After that, the water level of the reservoir slowly declined. By the end of March 2009, the water level had fallen back to 159 m ASL, then to 155 m ASL at the end of May and to 145 m ASL on 10 June 2009. During this period, 196 landslides and reservoir bank deformation occurred in TGRA. The former included the November 2008 North Nierwan landslide in Zigui County, the April 2009 Liangshuijing landslide in Yunyang County and the October 2009 Taping landslides in Wushan. Overall, the landslides and bank deformation caused the cracking of buildings and roadways located on the reservoir banks, affected 24,000 residents and posed a threat to shipping in the Yangtze River.

4.1.5. Assessment of other TGRA geohazards

4.1.5.1. Rock avalanche. Fluvial erosion, excavation and differential weathering represent important factors in the formation of rock avalanches in the TGRA. Under the effect of these factors, caves developed at the slopes' feet, leading to deformation and subsequent failure such as crack opening, rock mass tilting and rock avalanches (Dong et al., 2010; Huang and Gu, 2017).

The assessment of rock avalanches in TGRA mainly focused on unstable rock masses, which had formed through tensile fracturing and deformation. Block theory method, limit equilibrium method and numerical simulation have been used for stability analysis of unstable rock mass in TGRA (Zhou, 2016). Solid-liquid coupling computational fluid dynamic model was applied to study the deformation process of this type of geohazards (Yin et al., 2015a,b). Discrete element methods, capable of considering the distribution of fractures in unstable rock mass, were also employed frequently (Le et al., 2014).

4.1.5.2. Reservoir-induced earthquakes. Monitoring data demonstrated that water storage in TGRA can induce earthquakes. Many studies were conducted to investigate the formation mechanism of reservoir-induced earthquakes. The results indicated that the spatial distribution of reservoir-induced earthquakes was closely related to the presence of faults and karst caves. The friction coefficient of fault zone materials generally decreased along with the rapid infiltration of water caused by the impoundment. This often led to fault movements and induced earthquakes. For example, following the impoundment, many earthquakes occurred near the Xiannvshan fault (Li, 2013).

A comprehensive evaluation was conducted to address the issue of reservoir-induced earthquakes in TGRA. The area near the dam site with crystalline rocks (Fig. 1) was considered to be at moderate risk of reservoir-induced earthquakes. In this area, earthquakes were recorded near the faults. The area extending from the east of Zigui to Fengjie included faults and karst caves and was considered a high-risk zone of reservoir-induced earthquakes. In this area, many earthquakes occurred following the impoundment (Yi et al., 2012). The area extending from Fengjie to the west part of TGRA with Mesozoic red sandstones and mudstones was considered to be at low risk of reservoir-induced earthquakes, as it contained fewer faults. Few earthquakes were recorded in this area after the impoundment.

4.1.6. Landslide-induced impulse waves

Impulse waves were one of the forms of secondary disasters associated with TGRA landslides. The 2003 Qianjiangping landslide, which occurred shortly after the water level had risen to 135 m ASL following the first impoundment, induced an impulse wave as high as 30 m. Studies of landslide-induced impulse waves in TGRA focused on two issues, i.e., the kinematic characteristics of landslides and the propagation of impulse waves. The kinematic characteristics of landslide represent the basic input for the studies on impulse waves and, therefore, many past works focused on the landslide velocity and movement processes (Yin et al., 2015a,b; Huang et al., 2014). Physical model experiments and numerical simulations of the real cases, such as the Baishuihe and Gongjiafang landslides, were conducted to investigate the propagation characteristics of impulse waves (Huang et al., 2012). Together with the velocity and geometry of the landslides, the geomorphic conditions of the valleys were considered to assess their effects on the attenuation of impulse waves (Huang et al., 2016; Yi et al., 2012).

4.2. Prevention and control of TGRA geohazards

To ensure the safety of people and the operation of Three Gorges Dam, many geohazards prevention and control projects were implemented during and after the construction of the Three Gorges Hydropower station. Aiming at the key scientific issues governing landslide prevention and control, numerous theoretical and application-oriented studies explored TGRA landslide mechanisms and mitigation methods.

4.2.1. Prevention and control of landslides

More than 4,000 landslides and unstable slopes are present in TGRA. The common measures to prevent or control landslides in TGRA include drainage, slope re-profiling and unloading, construction of anti-slide piles, anchors, lattice beam and composite retaining structures (Zhang et al., 2014a,b).

Surface drainage, a simple but often effective method for landslide prevention, is widely applied in TGRA. In addition, subsurface drainage is also adopted in some larger and deeper landslides.

The Huanglashi landslide located in the Badong County is a successful example of the hazard mitigation and control by drainage. The landslide has a total volume of 18 million m^3 and complex hydrogeological and engineering geological conditions (Guo et al., 1999). The groundwater variation was found to have a strong influence on the stability of the Huanglashi landslide. Thus, a drainage system was adopted to stabilize and control further development of the landslide (Fig. 8). The controlling schemes were implemented as follows. First, a row of linearly distributed wells was established on the middle part of the Huanglashi landslide. It contained 33 wells with a distance between the wells ranging from 5 m to 10 m. Then, an adit to collect water beneath the sliding zone was installed. Water flowed into the adit through drainage wells, then into surface ditches. Based on the monitoring and observations reported by Tang (2007), the adopted control measures proved effective.

Engineering measures including slope re-profiling and reinforcement systems (such as anti-slide piles and anchors) were often adopted for landslides with significant movements. The Hongshibao landslide, a demonstration project of the landslide mitigation in TGRA, was reinforced using multiple engineering countermeasures. Given its huge

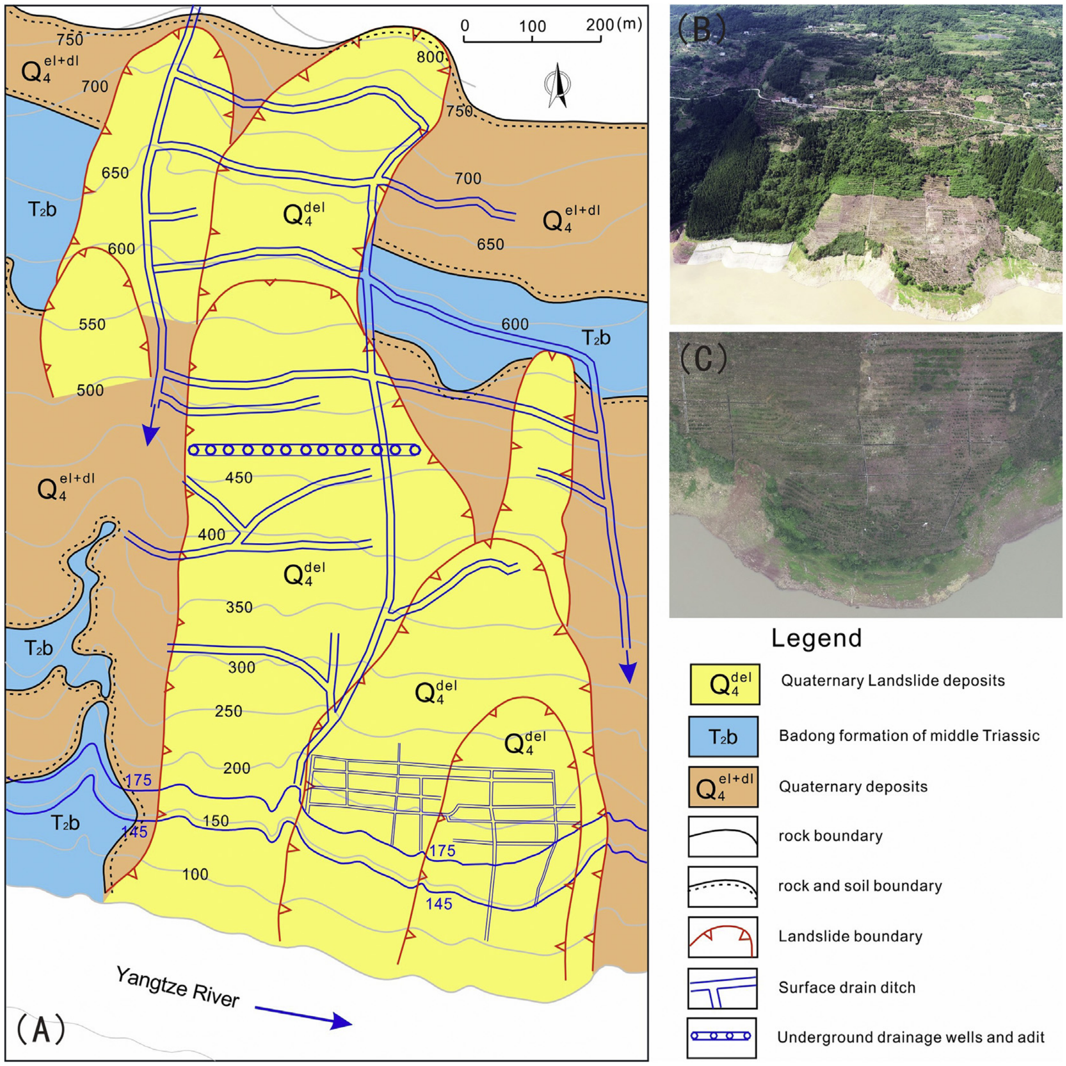

Fig. 8. (A) Drainage system used to stabilize the Huanglashi landslide, whose toe is affected by TGR water level fluctuations (note the 145 m and 175 m contours); (B) Full view of the Huanglashi landslide; (C) Aerial photo showing surface drainage system on the lower part of the Huanglashi landslide.

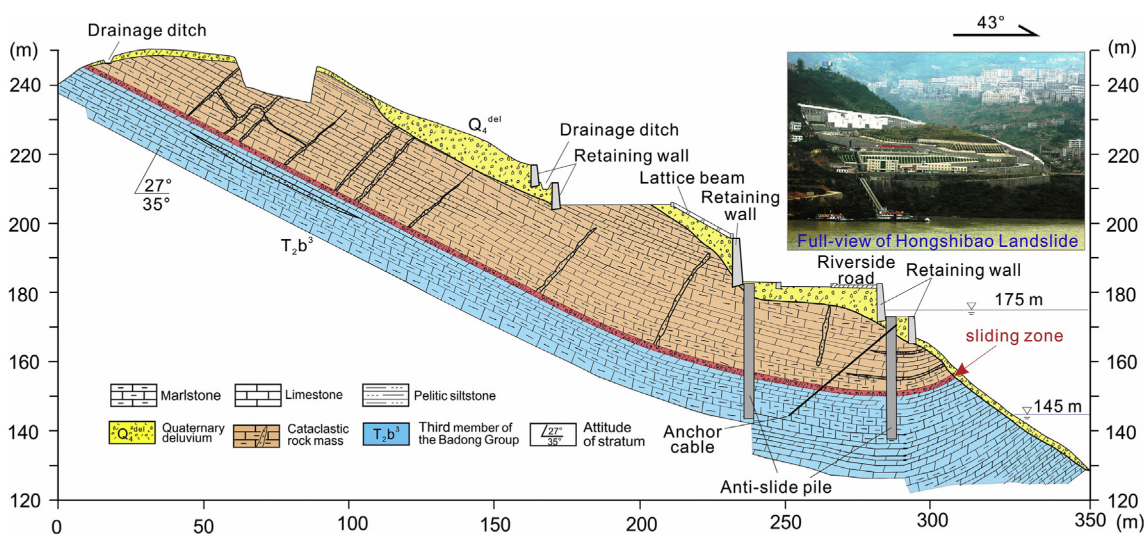

Fig. 9. Cross section of the Hongshibao landslide, whose toe is affected by fluctuations of the TGR level. Drainage ditches, retaining walls, lattice beams and anti-slide piles were constructed to stabilize this actively creeping landslide.

volume, the Hongshibao landslide represented a potential threat for the construction of the Badong oil depot. The protection measure that was found most effective included cantilever piles and anchor-piles (Fig. 9). A total of 52 anti-slide piles with lengths of 28 m–40 m, spacing of 8 m, and section size of 2 m × 3 m, were arranged in two rows. The additional measures were slope re-profiling, retaining wall, lattice beam and drainage ditch (Fig. 9).

Stabilizing piles were among the most commonly used and effective measures of landslide mitigation and control in TGRA. Many studies focused on the theoretical aspects and analysis of stabilizing piles. Numerical simulation methods, laboratory and in-situ tests were adopted to investigate the landslide thrust, interaction mechanism between stabilizing piles and landslides, and design optimization (Dai, 2002). The landslide evolution process that accounts for water fluctuation was also considered in the landslide thrust analysis (Jia et al., 2009).

Interaction mechanisms between stabilizing pile and landslide includes those between stabilizing pile and sliding mass (pile-soil interaction) and those between stabilizing pile and bedrock (pile-rock interaction). Both are important to optimize the design of stabilizing piles. Soil arching effect was considered in the study of the mechanism of pile-soil interaction (Tang et al., 2014; Zhang et al., 2018). As regards the pile-rock interaction, physical model tests and numerical studies were often employed. For example, using physical model tests, Li et al. (2016a, b) studied the behavior of stabilizing piles with different embedded lengths in bedrock with a strong upper layer and a weak lower layer.

Design optimization is an important aspect of stabilizing pile design. Theoretical and numerical methods based on soil arching effects were commonly used to optimize the size of cross section and spacing of piles (Li et al., 2016a, b; Wu et al., 2017). To determine the optimal pile length, a deformation control principle was developed based on the multi-layer subgrade coefficient method and physical model tests (Li et al., 2019a,b). To determine the optimal pile location, theoretical and numerical methods that consider safety requirement, critical slip surface, and stress and deformation of stabilizing piles were commonly adopted (Lei et al., 2006; Li et al., 2017). In addition, optimal plane arrangement schemes were investigated (Li et al., 2015).

4.2.2. Prevention and control of rock avalanches

Unstable rock masses are widespread in TGRA due to the presence of steep slopes and fractures. The commonly used methods for rock avalanche prevention and/or control include drainage, anchoring and slope re-profiling. The Lianziya unstable rock mass project was a successful example of the prevention and control of rock avalanche in TGRA.

The Lianziya rock mass, of approximately 260×10^4 m^3 volume, is mainly composed of massive thick limestone and has a steep topography. For steep and unstable rock masses, measures such as anchor cables, lattice anchors and spray anchors are usually adopted. Guo et al. (1999) documented a scheme of massive prestressed anchor cables used to stabilize the Lianziya rock mass (Fig. 10).

4.2.3. Prevention and control of other geohazards

In addition to landslides and rock avalanches, other geohazards such as debris flow, ground subsidence and ground fissures were observed in TGRA. In fact, the Badong County, Zigui County and Yiling District were severely affected by debris flows triggered by rainstorms. The presence of landslide deposits, artificial slag and slope erosion were important contributing factors. Dredging ditches, building dams and backfilling ditches were the primary engineering measures adopted to control the debris flows. For ground subsidence and ground fissures (Yin et al., 1999), engineering measures, such as grouting and filling, were often adopted to prevent the damage of rock mass structure. Finally, as part of a comprehensive prevention and control scheme in TGRA, monitoring and early warning systems were usually installed.

5. Geohazard monitoring and forecast in TGRA

5.1. Framework of geohazard monitoring and early warning system

The monitoring and early warning systems play an important role in the prevention and mitigation of TGRA geohazards. These systems are generally composed of several sub-systems such as the elementary monitoring system, the comprehensive monitoring system and the early warning system.

The elementary monitoring system is organized and operated by local governments. It relies on the geological monitoring stations and the participation of local residents. The main purpose of this elementary and local system is to perform quick inspection to identify imminent dangers from geohazards.

The comprehensive monitoring system relies on different measurement technologies such as global positioning system (GPS), remote sensing (RS), borehole inclinometers, landslide thrust force monitoring, groundwater monitoring and crack monitoring. Such comprehensive system provides a scientific basis for geohazard forecasting and warning.

The early warning system mainly consists of geohazard databases, GIS-based geohazard prevention decision support system, and network-based geohazard information management system. These systems provide important support for the effective risk management and mitigation of TGRA geohazards.

5.2. Geohazard forecast in TGRA

Temporal and spatial forecasting represent two main parts of geohazard forecast in TGRA. Short-term to long-term forecasting is provided and warning criteria are established. Spatial forecasting mainly focuses on risk assessment.

Landslides represent the main topic of researches on geohazard forecasting in TGRA. Short-term landslide forecast mainly aims at the determination of critical sliding time, while long-term forecast focuses on the prediction of long-term deformation based on displacement-time series under the effects of various external and internal factors. The forecast methods can be classified into four categories: physical-mechanical forecast methods, traditional non-intelligent methods, intelligent methods and probabilistic forecast methods.

Physical-mechanical forecast methods, such as the Saito model, creep-spline joint model and Voigt model, are usually adopted for forecasting the critical sliding time. Traditional non-intelligent methods, intelligent methods and statistical forecast methods are mainly applied in long-term forecasting of geohazards. The traditional non-intelligent methods such as grey theory, time series and Kalman filter were often used to build prediction models for long-term forecasting of landslides in TGRA (Li et al., 2006; Lu and Wang, 2008; Xu et al., 2011). With the rapid development of artificial intelligent algorithms, the intelligent methods such as artificial neural network (ANN) and supporting vector machine (SVM) have increasingly been employed in the long-term forecast of landslides (Bai et al., 2009; Du et al., 2013; Peng et al., 2014; Ma et al., 2017a,b). The intelligent methods are effective in dealing with complex problems related to landslide prediction. In recent years, the effect of uncertainty in landslide forecasting has been well recognized, and probabilistic models that can consider explicitly the uncertainty have been developed (Lian et al., 2016; Ma et al., 2018).

The aforementioned methods are mainly used for predicting the landslide behavior. For effective mitigation, an early warning criterion is also required to issue timely alarms. The early-warning criteria for geohazards in TGRA usually rely on macroscopic precursors, stability indices, displacement data and environmental conditions. Examples of macroscopic precursors include significant deformation of ground surface and buildings, collapse of landslide toe and sudden variation of subsurface water level. These phenomena are distinct and generally

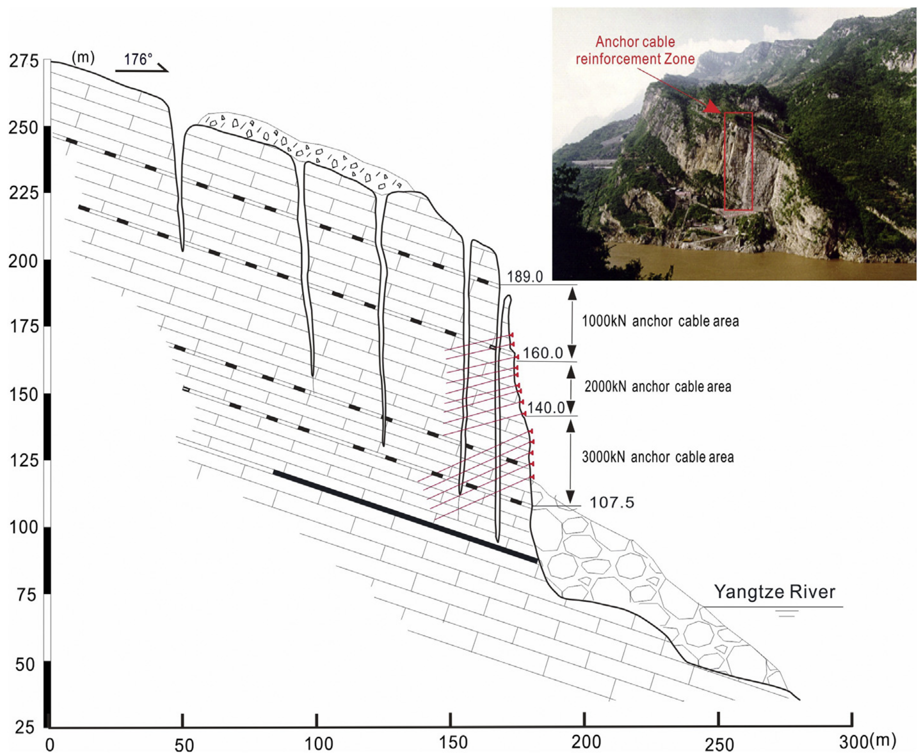

Fig. 10. Cross section of the unstable Liangzia rock mass (after Guo et al., 1999); large anchor cables (red lines) were installed to stabilize this rock mass. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

visible during the critical sliding stage and can be detected by local residents. Criteria based on the stability indices include factor of safety and reliability index, derived through the deterministic and probabilistic analysis respectively (Hu et al., 1996). Displacement data represent the most direct and accessible information obtained via landslide monitoring; thus, many criteria have been proposed based on displacement data, e.g. displacement rate and acceleration (Yuan et al., 2015) and displacement vector angle (He et al., 2003). Criteria based on the environmental conditions are mainly related to rainfall and TGR water level fluctuation. The maximum 24-h rain intensity and the decline rate of reservoir water level are effective indicators for early-warning of TGRA landslides (Ni et al., 2013).

Temporal forecast of geological hazards is critical for their mitigation, which is the most challenging part in hazard prevention. Nevertheless, several successful forecasts have been documented. For example, the Xintan landslide (Fig. 11) that occurred in the early morning of 12 June 1985 was successfully predicted in advance and 1371 people were evacuated the night before the disaster struck. This event provided a valuable experience for geohazard forecasting in TGRA.

6. Large-scale in-situ experimental facilities

6.1. Badong in-situ experimental station

The Badong in-situ experimental station is located in the Huangtupo landslide area, which is the largest reservoir landslide by volume in TGRA (Tang et al., 2015a,b). This experimental station is the largest underground landslide monitoring and testing facility in the world built to foster research, teaching, academic exchange on TGRA geohazards. The station was designed and constructed, and has been operated, by the China University of Geosciences since 2012. Over 10,000 people with a variety of geology-related backgrounds from > 20 countries have visited this experimental station.

The Badong experimental station consists of a tunnel complex and a series of monitoring systems (Fig. 12). The tunnel complex, built in the Huangtupo riverside sliding mass #1, consists of a main tunnel with a length of 908 m and a width of 5 m, five branch tunnels (5 m to 145 m long, 3.5 m wide), two test tunnels, and 35 observation windows. The test tunnels exposed the sliding zones of the landslide, facilitating their direct observation and the execution of scientific experiments, such as large-scale in-situ mechanical tests and deep deformation monitoring. The monitoring systems measure deformation as well as hydrologic, meteorological and hydro-chemical variables. The deformation system is composed of a slope surface displacement measurement unit and an underground displacement measurement unit. The slope surface displacement unit includes a number of GPS (Global Positioning System) and BDS (BeiDou Navigation Satellite System) measurement points, as well as an IBIS-FL (Interferometric Radar) monitoring system (Fig. 12). The underground displacement unit includes nine deep inclinometer boreholes, a number of crack meters installed on the ground and the walls of tunnels, and many hydrostatic level gauges that measure the settlement of the tunnels in the sliding mass. The hydrologic system includes a number of devices that allow for observation of the water level of the Yangtze River, the ground water level and water discharge of the tunnels (Fig. 12). A small meteorological station is located on the landslide and provides rainfall data. All these monitoring devices, except the inclinometers, have recently been updated with real-time acquisition and automatic transmission features.

6.2. Majiagou in-situ experimental station

The Majiagou in-situ experimental station is located in the Majiagou landslide area in Zigui. This experimental site provides a platform to study the landslide stability during the reservoir operation, the interaction mechanism between the landslide and stabilizing structures, and the optimization design of stabilizing structures (Hu et al., 2017). An integrated, in-situ multi-parameter monitoring system was designed and installed during the test pile construction. The system included surface displacement and borehole monitoring, as well as experimental

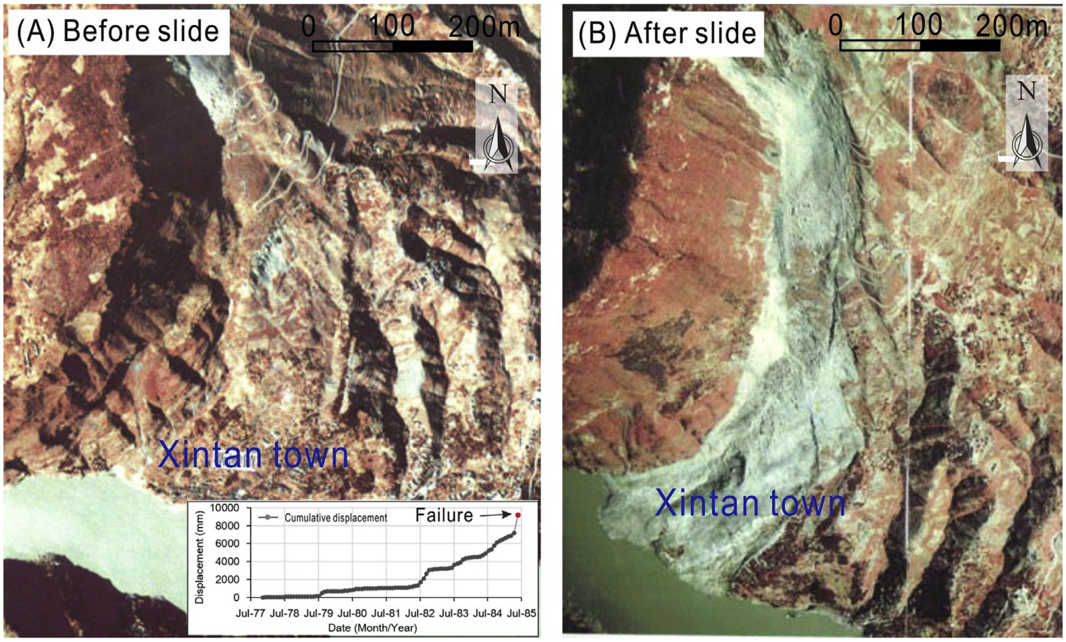

Fig. 11. Aerial images of the Xintan landslide before and after the event.

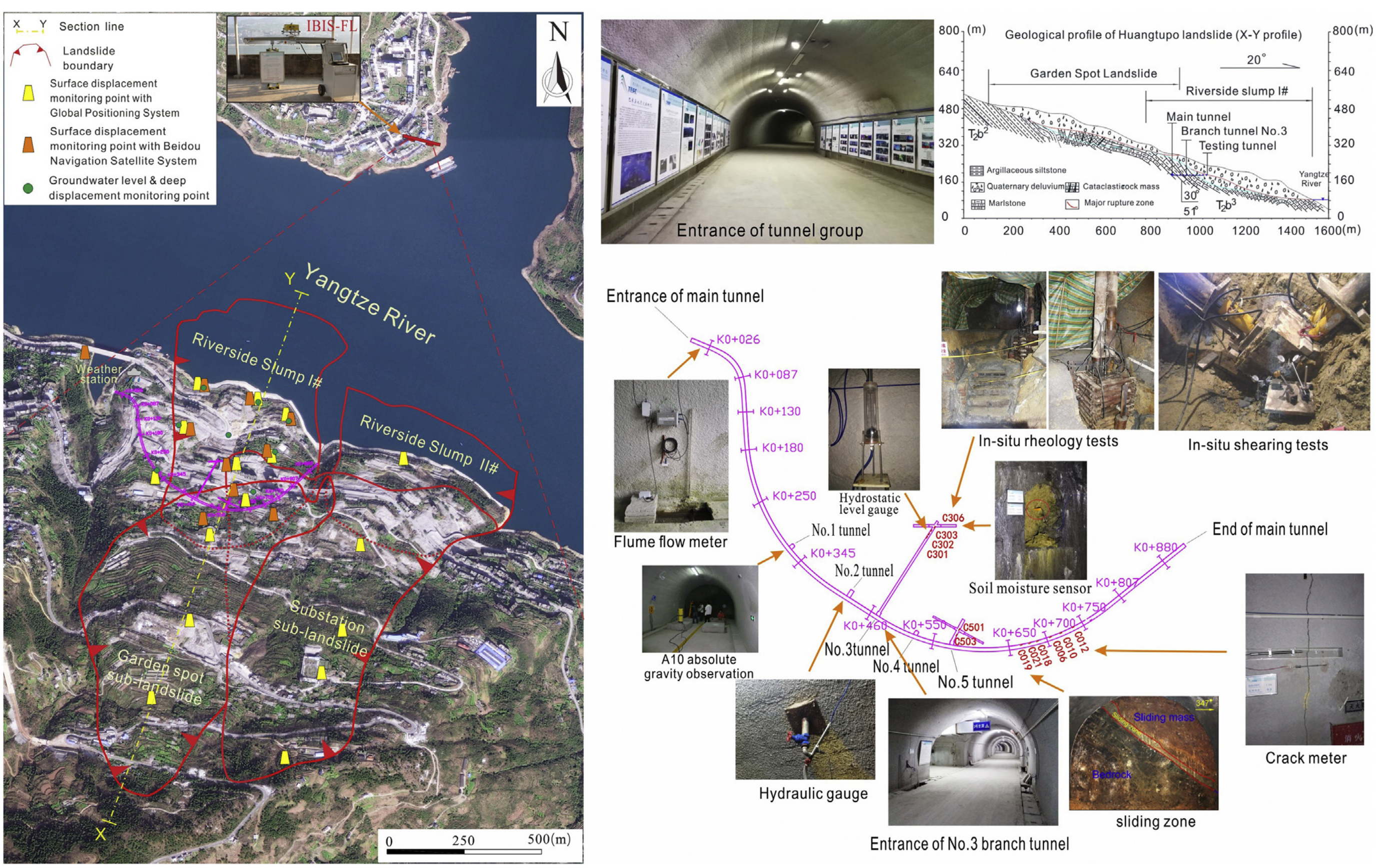

Fig. 12. Badong in-situ large-scale experimental station.

pile monitoring (Fig. 13).

The surface deformation monitoring relied on five GPS stations and two fiber-sensing cables. The borehole monitoring system includes 15 boreholes, distributed along the main sliding direction, with different types of sensors installed to measure the deep displacement of the Majiagou landslide. The monitoring of the experimental piles (40 m long) relied on earth pressure gauges, stress gauges, strain gauges and fiber sensors. The earth pressure gauges were positioned on the surface of the piles to measure the lateral earth pressure. The stress gauges, strain gauges and strain-sensing fibers were installed in the stabilizing piles to measure the axial stress and the deflection of the piles. In each test pile, 26 stress gauges and strain gauges were installed to measure

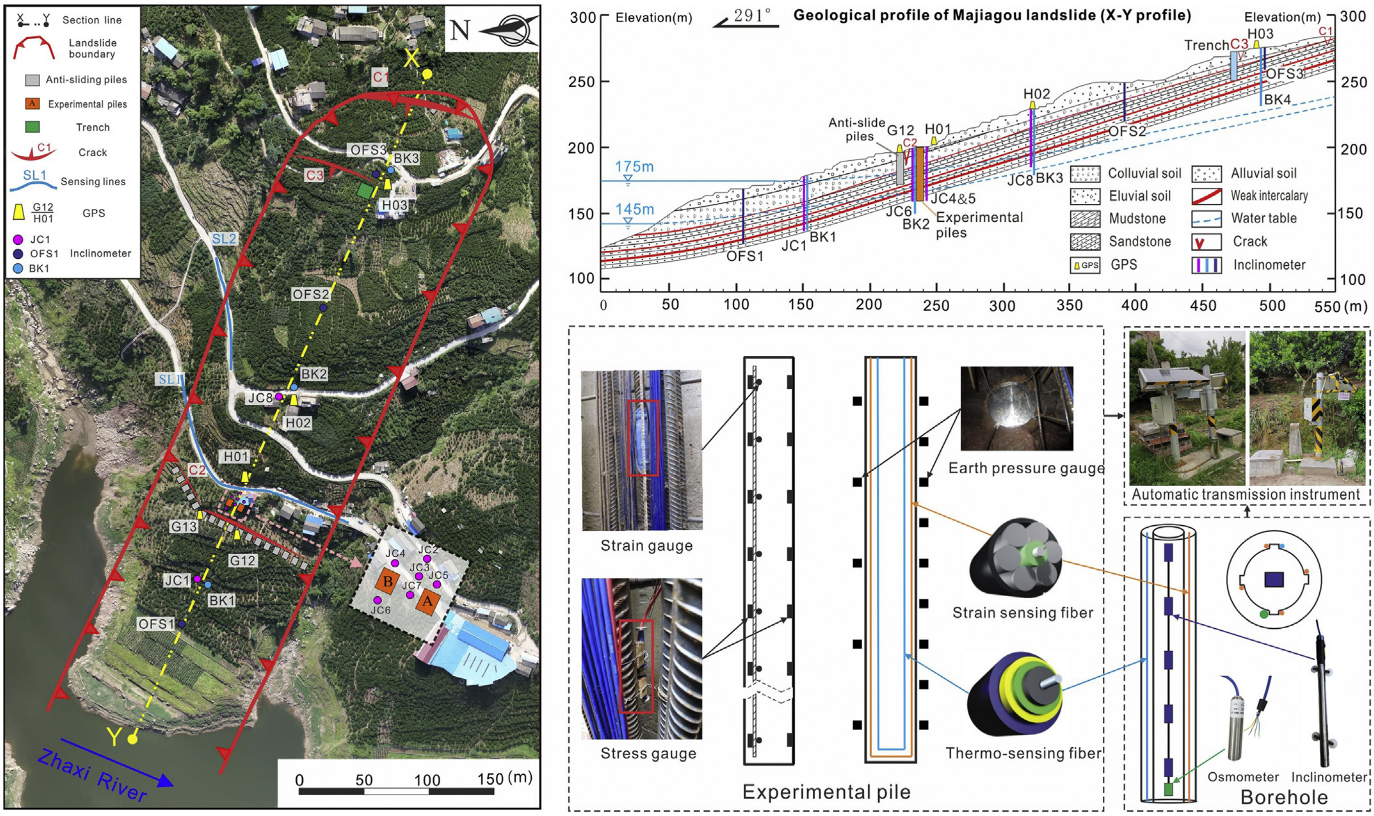

Fig. 13. Majiagou in-situ experimental station.

the longitudinal pile stress and strain. The thermo-sensing fibers were distributed along the experimental piles to monitor the change of the temperature within the landslide.

The Majiagou in-situ experimental site, together with the Badong in-situ large-scale experimental station, offers engineering geologists a unique opportunity to gain experience in the field of reservoir-related geohazard prevention, reduction, and mitigation.

7. Challenges and suggestions for future research

Past decades of research on TGRA geohazards has produced a tremendous amount of valuable scientific-technical literature. The lessons learned have improved our understanding and capability in preventing geohazards and mitigating their effects. Although achievements have been significant, many challenges still exist. Many more efforts and resources are required for future research to meet these challenges. A list of challenges and suggested topics is provided in the following to stimulate further research.

(1) Long-term stability assessment of reservoir landslides

The past research mainly focused on the aspects of rheology and residual strength properties of the sliding mass and slip surface. However, landsliding involves a process of dynamic stress change and deformation under the effects of external factors. These dynamic changes should be considered and incorporated explicitly in the long-term stability assessment of landslides. In addition, the long-term stability assessment of landslides stabilized by engineering structures needs further research.

(2) Control countermeasures for huge reservoir landslides

More than 30 huge landslides (volume > 10 million m^3) were identified in TGRA. Many of these landslides, such as the Huangtupo and Baishuihe landslides, are still active with a cumulative displacement of several meters and pose a great threat to the Yangtze River navigation. However, traditional controlling methods, such as anti-slide piles and anchor cables, are difficult to implement due to the size of these landslides. It is extremely urgent to develop effective countermeasures to control and manage these huge landslides.

(3) Multi-parameter integrated monitoring system for reservoir geohazards

The evolution process of landslides can be more accurately revealed through the integrated acquisition of multi-parameter data that may be cross-correlated. However, the current monitoring systems usually consist of different monitoring devices that obtain data independently. Therefore, an integrated monitoring platform with multi-parameter data acquisition capability is needed. The integrated and correlated information regarding the evolution of different fields, such as reservoir seepage, stress, and surface/subsurface displacement offers a stronger basis for a more accurate geohazard analysis. Research into integrated monitoring technology and equipment, as well as into new algorithms, to utilize effectively the multi-parameter correlated information in the rapid assessment of landslide stability and deformation is urgently needed.

(4) Geohazard prediction and warning using big data analytics and artificial intelligence

With the huge amount of data collected through various monitoring systems in TGRA it has become a challenge to efficiently derive useful information and provide an accurate and fast prediction of geohazards. Recent advances in big data analytics and artificial intelligence technology offer tremendous opportunities for faster and better predictions of geohazards, and more effective warning systems. Research exploiting these modern technologies for the mitigation of TGRA geohazards is expected to bear fruitful outcomes and is therefore warranted.

(5) Geohazard mitigation based on "Green Concept"

The Green Concept refers herein to "cherish live, protect the environment and obey the law of nature". The concept is becoming increasingly popular and necessary for the sustainable development of a region such as TGRA that has limited resources and constantly faces potentially disastrous geohazard threats. When it comes to the prevention and mitigation of geohazards in TGRA, it is essential that the engineering works exist in harmony with nature. More research on incorporating the sustainability concept into the adopted strategies and schemes for the prevention and mitigation of TGRA geohazards is certainly warranted.

8. Concluding remarks

TGRA geohazards have been a major focus of the engineering geology research and development in China in the past few decades. These efforts have led to better knowledge and practice in the prevention and control of TGRA geohazards. This paper provided a comprehensive review of the geohazards related articles and research developments in the past decades. First, the studies of landslide evolution mechanisms, centered on the dynamic characteristics of major influencing factors and the geotechnical properties of slide-prone masses, provided insights into the formation and evolution of TGRA geohazards. Then, the research on the geohazard prevention and control measures, such as deep drainage, anchors, and anti-slide piles, offered valuable experience for geohazard management in TGRA. The studies on the monitoring and early warning systems further contributed to the prevention and mitigation of disasters from geohazards. Finally, the development, construction and operation of the large-scale field experimental station (Badong station) offered a unique research opportunity for the advancement of knowledge on different aspects of TGRA geohazards, while providing a very useful platform for teaching the next generation of engineering geologists and for research collaborations among the engineering geology communities worldwide.

Despite the major advances in the research and development, challenges still exist in the prevention and mitigation of TGRA geohazards. These include issues such as the long-term stability assessment of reservoir landslides, the control countermeasures for huge reservoir landslides, the integrated multi-parameter monitoring systems for the acquisition of correlated information on reservoir geohazards, the geohazards prediction and warning using big data analytics and artificial intelligence, and the geohazard prevention and mitigation based on the green and sustainability concept. These challenges represent real opportunities for the engineering geologists in their pursuit of geohazards reduction and mitigation.

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