Reservoir impoundment and water fluctuations have endangered the stability of the reservoir bank slopes, which have experienced several small-scale shallow slides/collapses and few large-scale slopes with failures/deformations. Field investigations, unmanned aerial vehicle technology and site displacement monitoring dates are used to study the spatiotemporal distribution and mechanisms of the reservoir landslides within the Dagangshan reservoir. The reservoir landslides can be divided into two main types: shallow small-scale slides and unstable deformation slopes, which are clearly associated with reservoir impoundment and fluctuations of the water level. Small-scale slides/collapses are continually distributed along the river banks nearest to the water level, but deep-seated landslides have usually experienced a long history, and some obvious precursor phenomena may exist in the slopes. According to the recognition of deformational and failure evolutionary processes of large-scale slopes, and based on hydrology and geomechanics, two types of potential failure models (creep—shear—tension failure and toppling—tensile—shear model) are proposed to interpret the mechanisms of the deformation slopes in the Dagangshan reservoir. Furthermore, some preliminary discussion is presented concerning the non-significant development of landslides in the Dagangshan reservoir that are also associated with smaller water fluctuations due to the daily regulation type of the reservoir.

1. Introduction

A large number of massive hydropower stations have been constructed in south-western China, including the Jinping-I and Jinping-II Hydropower Stations on the Yalong River, the Dagangshan Hydropower Station on the Dadu River, the Maoergai
Hydropower Station on the Heishui River and the Three Gorges Hydropower Station on the Yangtze River (Zhou et al. 2010; Jiao et al. 2014; Gui et al. 2016; Yin et al. 2016). After the construction of a high dam, the water storage and constantly fluctuating water have an adverse influences on slope alone the river banks and lead to changes in the local climate and ecological environment (Wang et al. 2004; Mazaeva et al. 2013; Zhou et al. 2016b) to accelerate the adverse influences on safety of slope (Hu et al. 2015; Babanouri and Dehghani 2017; Sun et al. 2017). These reservoir landslides pose a great threat to the safety of hydropower stations (especially high dams), coastal infrastructure and human life. In addition, they may engender a chain of subsequent serious disasters, including landslide surges, blocked rivers and the formation of dammed lakes (Xu et al. 2015; Zhang et al. 2015; Gomez et al. 2016; Huang and Wang 2017). Therefore, reservoir landslides have been widely investigated in recent years, and related studies on their spatiotemporal distribution characteristics and the triggering mechanisms of landslides can help us to formulate hazard prevention and mitigation measures (Yin et al. 2015; Zhou et al. 2016a; Iqbal et al. 2017).

Numerous catastrophic reservoir landslides have been reported in previous studies, which have attracted substantial attention from governmental departments and related researchers (Schuster 1979; Austin et al. 2013; Zhou et al. 2016b). For example, a catastrophic landslide occurred in the Vajont reservoir in 1963, which caused more than 2600 casualties due to a gigantic landslide surge that breached the 140 m dam (Qi et al. 2006; Petronio et al. 2016). In 2003, the Qianjiangping landslide occurred on the Yangtze River of China, which caused a landslide-generated wave with a maximum height of 20 m, leading to more than 20 deaths and an interruption of water transport along the Yangtze River (Yin et al. 2015). As an effective prerequisite for hazard prevention and mitigation, it is very important to recognize landslides, including their distribution and triggering mechanisms. For instance, Yin et al. (2016) interpreted the spatiotemporal distribution of reservoir landslides within the Three Gorges reservoir, classified all of the landslides therein into five failure patterns, and proposed a triggering mechanism for major landslides, which represents a great contribution to landslide treatment. By employing an interpretation of air photography in conjunction with field investigations and remote sensing, Iqbal et al. (2017) took the landslides in the Xiangjiaba reservoir (which seriously affected the completion of the hydropower station located therein) as an example to analyze the distribution characteristics of reservoir landslides. In addition, the triggering mechanisms of reservoir landslides are generally associated with external water conditions (e.g. rainfall, reservoir impoundment and fluctuations of the water level); therefore, changes in water conditions may especially raise the possibility of landslide occurrence within a reservoir.

As the above analysis has mentioned, the major triggering mechanisms for reservoir landslides include heavy rainfall, strong earthquakes, fluctuations of the water level and manmade disturbances (such as excavations of the slope toe and blasting vibrations). Most of the previous studies have concluded that reservoir-induced landslides primarily occur while the reservoir is being filled or within a few years following the completion of the project. This is especially true during the initial impoundment phase, which is because of a sudden transform of the rock-soil material
from unsaturation to saturation, and this process can likely change the mechanical properties of the geo-materials and the slope seepage field (Riemer 1992; Jiao et al. 2014; Sun et al. 2016; Yin et al. 2016). Meanwhile, water fluctuation plays an important role in the occurrence of reservoir landslides, especially due to the rapid drawdown of the water level, during which time the drag force alone the sliding zone in addition to excessive pore water pressure appears to endanger the slope stability (Lane and Griffiths 2000; Berilgen 2007; Xia et al. 2013). Moreover, some catastrophic reservoir landslides, including the Outang and Hongyanzi landslides, were triggered by coupled factors (e.g. combinations such as heavy rainfall with rapid drawdown and rapid drawdown with manmade disturbances) induced by the coupling of factors related to rainfall and water fluctuations (Zhou et al. 2016b; Huang and Wang 2017).

In addition to external influences, reservoir landslides are also closely associated with the presence, type and abundance of reservoir bank slopes (especially for topographic and geological conditions). South-west China is a relatively fragile geological area with a wide distribution of Quaternary deposits, and the shallow rock masses are generally represented by strong weathering and unloading, which are likely to increase the possibility of reservoir landslides. In this paper, the reservoir landslides in the Dagangshan reservoir are taken as an example to study the spatiotemporal distribution of landslides before and after impoundment by integrating field investigations with unmanned aerial vehicle (UAV) technology. Meanwhile, three typical slopes are used to summarize the deformation characteristics and triggering mechanisms of the reservoirs of bank slopes. Finally, some preliminary discussions are presented with regard to the comparison of development extent of landslides in several reservoir areas.

2. Background

The Dagangshan Hydropower Station is located midstream within the Dadu River, which originates from the Qinghai Province (Western China) and is the second tributary of the Yangtze River. A large double-curvature arch dam with a height of 210 m was constructed on the Dadu River, which formed an immense reservoir with a total storage capacity of $7.42 \times 10^8$ m$^3$ and a regulating storage capacity of $1.17 \times 10^8$ m$^3$ with a storage regulating ratio of 15.8% (i.e. the regulating storage capacity/total storage capacity), which is typical for a daily regulation type of reservoir. The normal water level rests at an elevation of 1130 m, while the dead water level sits at an elevation of 1120 m, and the maximum fluctuation of the water level is 10 m. The upper and lower regions of the reservoir are adjacent to Luding County, Ganzi County and Shimian County, as well as Ya’an in Sichuan Province, as shown in Figure 1. The Dagangshan Hydropower Station is the 14th cascade hydropower station on the Dadu River, and its main objective is to generate electricity with a 2600 MW installed capacity. The drainage area of the Dagangshan reservoir is 62,727 km$^2$. A large area of mountains (i.e. the toe of the slopes) is submerged within the reservoir water, thereby increasing the possibility of landslides.
2.1. Geological conditions

The study area is located in south-west China and is a typical mountainous region with a topography characterized both by high, steep mountains and canyons. Figure 2(a) describes the stratum lithology and regional tectonic properties of the study area. The study area belongs to the central region of the south-western Sichuan Province, which represents a transition from the south-eastern margin of the Tibetan Plateau to the south-western Sichuan Basin. The main stratigraphy of this area is represented by the western Bayan Har strata, which exhibits a set of underdeveloped Proterozoic-Mesozoic sedimentary rocks, and by the eastern Yangtze strata, which is mainly composed of Permian-Triassic metamorphic rocks that are bounded by the Jinping fault (F19) and the northern section of the Xiaojin River fault (F13). In addition, the hub area and the head of the reservoir are located in the Huangchaoshan fault block, which is excised by the Moxi fault (F11), the Dadu River fault (F24) and the Jinping fault. The Moxi fault and the Dadu River fault pass through the hub area with lengths of approximately 4 km and 4.5 km, respectively, which leads to a poor structural stability. As shown in Figure 2(a), large seismic belts are distributed along the Dadu River fault and the Moxi fault near the reservoir area, which indicates that the study area has been influenced by strong historical earthquake events, for example 1786 Kangding earthquake (Dai et al. 2006).

The study area is located at the junction of the Yangtze platform and the Bayan Har geosynclinal fold system and has experienced the effects of magmatism and intense tectonism. The exposed stratum exhibits a complex evolutionary history and presents the characteristics of multiple types and multiple causes of deformation. The stratigraphic bedrock is mainly composed of basic-ultrabasic rock, which consists of diorite and granite from the Jinning-Chengjiang period. Meanwhile, the Sinian,
Devonian and Permian strata are widely distributed along the right bank and constitute a set of shallow metamorphic terrigenous clastic rocks as well as carbonate rocks. Furthermore, the Triassic Baiguowan group (T<sub>3bg</sub>) is only distributed locally in the middle section of the reservoir and the tail section of the reservoir, both sides of which are restricted by the eastern and western branches of the Dadu River fault. Simultaneously, due to the influence of the Dadu River fault, soft lithologies (sandstone and shale) and the effects of weathering and unloading, this stratum exhibits well-developed structural surfaces and fractures (as shown in Figures 2(b,c)). In addition, there are large volumes of Quaternary deposits on both sides, which present different distinct historical sedimentary layers (as are shown in Figures 2(d,e)), which were mainly initiated as alluvium, diluvium and colluvium, or as ancient landslides. These landslides and/or slope instability problems mainly occur in Quaternary deposits, strongly weathered and fractured rock masses, and soft rock masses with heightened sensitivities to water.

Figure 2. Geological conditions in the Dagangshan reservoir: (a) stratum lithology and regional tectonic properties; (b) the Triassic Baiguowan group with well-developed structural surfaces and toppling/bending phenomena; (c) strongly weathered and fractured rock mass; (d) widespread quaternary deposits; and (e) distinct historical sedimentary layer.
2.2. Hydrological and meteorological conditions

Two hydrological stations (Luding and Shimian) are situated at the upper and lower reaches of the Dagangshan reservoir, respectively, which provided references for the hydrological and meteorological conditions of the study area (as shown in Figure 3(a), the average rainfall data in history). According to the statistical data collected by these two stations, the rainy seasons are mainly concentrated between April and September, wherein more than 70% of the annual rainfall occurs during these months. The maximum average monthly rainfall is approximately 120–140 mm in July, and the average annual rainfall is roughly 630–800 mm. The flooding seasons are mainly concentrated between June and September, and the annual maximum flow occurs in June or July. After impoundment, the water level rose from 1010 m in March 2015 to 1120 m in July 2015, after which operating conditions ranged from 1120 m to 1130 m. As shown in Figure 3(b), the water level sharply increased during the reservoir impoundment process and then fluctuated between elevations of 1120 m and 1130 m.

3. Spatiotemporal distribution of landslides

Under the effects from the adverse influences of the topographic and geological features within the study area, including steep slopes, widespread Quaternary deposits,
high-intensity earthquake-prone zones, softened Triassic sandstones and shales, and strongly weathered and fractured rock masses, several different scales of landslides have occurred within the Dagangshan reservoir as the consequences of reservoir impoundment, rainfall, manmade disturbances and fluctuations of the water level. Since the first impoundment to an elevation of 1120 m, several small-scale landslides have been observed continually along the river banks, which are nearest to the water level. After more than 1 year of hydropower station operation, some large-scale landslides characterized by large deformation and/or typical failure phenomena appeared in the Dagangshan reservoir. All of the landslides in the Dagangshan reservoir can be divided into two categories: shallow small-scale slides and unstable deformation slopes (i.e. displaying large deformation or potential failure but maintaining global stability, as shown in Table 1). The landslides in the Dagangshan reservoir are controlled by water storage, fluctuations of the water level, rainfall infiltration, manmade disturbances or coupled effects of the aforementioned. The spatiotemporal...
3.1. Temporal distribution characteristics

The Dagangshan Hydropower Station has been operating since May 2015. During the initial impoundment stage, the water level increased from approximately 1010 m to an elevation of 1120 m, and then slightly fluctuated between the elevations of 1120 m and 1130 m due to the operation of the hydropower station. After impoundment, the evolutionary trend of failure became increasingly obvious for many slopes along the banks, including the revival of previous landslides and new landslides. Specifically, obvious deformation characteristics were observed within the ancient landslide deposits along the Xinhua slope with a volume of approximately $7 \times 10^7$ m$^3$, which is when the water level reached 1120 m on 4 July 2015. As shown in Figures 4(a,b), some small-scale slides/collapses appeared near the surface of the water, and some tensile cracks were observed in the tailings of the slopes that were induced by the large deformation of the leading edge. During the rainy season, these destruction phenomena became more obvious. Meanwhile, the evolution of tension cracks in the Xinhua slope was further enhanced with an apparent water level drawdown between 30 May 2016 and 6 June 2016, with a decrease in the depth of 5.29 m at an average velocity of 0.77 m/d.

Furthermore, the rise in water level also resulted in new landslides and/or slopes with large deformation. One such example is the Zhengjiaping slope, which is a counter-tilt layer-softened rock slope developed within the Triassic Baiguowan group ($T_{3bg}$) that presented numerous cracks caused by large deformation and local collapse, and caused an interruption of road traffic due to a collapse of the highway slope after 30 April 2016. As shown in Figures 4(c,d), the aforementioned failure phenomenon mainly occurred on the side of the new highway (S211) and its upper reach, and is associated with the artificial excavation associated with the reconstruction of highway S211 and the rainy season within the Dagangshan basin from April to September. Apart from the Xinhua slope and the Zhengjiaping slope, the rest of the deformed slopes (Table 1) also exhibit collapses of Quaternary strata or fractured rock mass near to the water surface in response to the impoundment and fluctuations of the water level, but large-scale landslides are still not observed. On the other hand, as

Table 1. Basic conditions and failure characteristics for the seven large-scale deformation slopes in the Dagangshan reservoir.

| No. | Slope | Location | Distance to dam site (km) | Elevation (m) | Volume $(\times 10^4$ m$^3)$ | Failure characteristics |
|-----|-------|----------|--------------------------|--------------|----------------------------|------------------------|
| 1   | Mogangling | Right bank | 31.2 | 1110–1450 | 2400 | Local collapse |
| 2   | Lantianwan | Left bank | 28.5 | 1150–1400 | 3000 | Local collapse |
| 3   | Detuo | Left bank | 22.4 | 1140–1200 | 430 | Local collapse |
| 4   | Xinhua | Left bank | 14.6 | 1065–1420 | 700 | Large deformation, cracking, several shallow failures |
| 5   | Dagou | Right bank | 10.8 | 1055–1180 | 50 | Local collapse |
| 6   | Luojinggou | Left bank | 19.8 | 1095–1400 | 300 | Local collapse |
| 7   | Zhengjiaping | Right bank | 11.8–15.0 | 1115–1350 | 5,500 | Large deformation, cracking, several shallow failures |
shown in Figures 4(e,f), some shallow small-scale collapses are distributed along the river banks, which mainly occurred within shallow Quaternary deposits or fractured rock masses with strong weathering and unloading histories. These small-scale landslides pose lower threats to the safe operation of the hydropower stations. However, the slopes with large deformation and the potential for large-scale landslides pose greater threats to the safety of the reservoir, coastal infrastructure and human life.

The temporal distribution of landslides in the Dagangshan reservoir is clearly associated with reservoir impoundment and fluctuations of the water level. Rainfall infiltration also plays an important role towards inducing landslides, especially for shallow small-scale slides/collapses. Furthermore, manmade disturbances (e.g. the reconstruction of reservoir traffic road and blasting vibrations) provide an additional contribution to shallow collapses or slopes with large deformation. Shallow small-scale slides/collapses are generally sudden occurrences and transpire over a short period of time. However, deep-seated landslides are usually experienced over a long
period of history, and some obvious precursor phenomena may exist within the slope, such as tension cracks in the rear and/or sides of the slope, large deformation and collapses within the slope toe.

3.2. Spatial distribution characteristics

Technology employing UAVs was used to explore the spatial distribution of landslides in the Dagangshan reservoir. Combined with the images cached by the UAV, geological data and field investigations were utilized to divide the Dagangshan reservoir into three zones along the Dadu River. The first zone, with a length of 10.1 km, is composed of the main reservoir of the Dadu River as well as its tributary constituting the Yusha River, which extends from the dam site to the estuary of the Tianwan River (the first tributary on the right bank of the Dadu River). The terrain of this zone is that of an alpine canyon with a crooked river bank, and the slope is comprised of bedrock that primarily includes biotite, adamellite and syenite granite interspersed with a distribution of veins. Moreover, the reservoir rock masses present a fractured and blocky structure due to the intrusive contact interface and structural planes. However, the slopes in this zone show no visible deformation, and small shallow slides are formed alone within the fractured zone of diabase dykes.

Similar to the first zone, the second zone, whose reservoir bank is mainly composed of bedrock (including granite and diorite), also shows an alpine canyon but with a relatively flat river bank. As shown in Figure 5, the Tianwan River, Shiyue River and Wandong River are located within this zone, which has a length of 19.9 km from the estuary of the Tianwan River to the Shaba Segment. Here, the fault of the Dadu River is distributed along the main reservoir valley, and the Moxi fault passes through the Tianwan River and the Shiyue River. Along the bank of the Tianwan River, the rock masses are composed of Paleozoic–Proterozoic marble and dolomite and exhibit fractured and blocky characteristics within shallow rock masses. The geological conditions of the main reservoir are very complex and are characterized by a banded distribution of sands and shales of the Baiguowan group ($T_{3bg}$) along the Dadu River fault, a steeply dipping layered structure and a well-developed joint fissure. Due to these adverse geological conditions, some local toppling failures and large deformation in the slopes are well developed, including the Xinhua slope, the Dabiangou slope and the Zhengjiaping slope.

The last zone, which incorporates the Moxi River, extends from the Shaba Segment to the reservoir tail and stretches a length of 12.7 km. The valley is wider with well-developed terraces, Quaternary deposits and proluvium on both of the river banks. Moreover, the Dadu River fault is distributed along the left side of the valley. The reservoir banks are composed of bedrock and overburden, each of which accounts for approximately 50%. Here, the bedrock is mainly composed of granite and diorite as well as local sands and shales of the Baiguowan group ($T_{3bg}$). Small collapses and toppling deformations are well-developed in this zone, including the Mogangling slope that is developed towards the rear of the reservoir bank. However, the covering layers of the reservoir bank, which presents as terraced terrain, are composed of alluvium, slope deposits and pluvial deposits.
In summary, from the perspective of their spatial distribution, the landslides in the Dagangshan reservoir have the following characteristics: (a) most of the deformation slopes that present a greater threat are located in the middle and the tail of the reservoir, where the valley is wider; (b) the slopes with large deformation are developed in Quaternary deposits (such as the Xinhua slope), large block cataclastic boulder deposits (composed of granite and diorite) with relatively higher strength (such as Mogangling slope), soft rock masses (sandstones and shales, such as the Dagoubian slope) and soft rocks (sandstones and shales) with weak interlayers (such as the Zhengjiaping slope). Furthermore, as shown in Figure 5, the deformation slopes are basically presented within a linear distribution along the Dadu River fault and the Moxi fault with large seismic belts, which experience unfavourable geological conditions from the perspective of the regional tectonism.

4. Deformation and failure of large-scale slopes

The deformation and failure processes of the reservoir bank slopes in the Dagangshan reservoir exhibit an evolutionary process from shallow slides to deep-
seated slides. As a consequence of erosion of shallow deposits, long-term water softening and rainfall infiltration, the appearance of local collapses, large deformation and tension cracks is observed within the rear of some large-scale slopes. Here, three typical large-scale slopes with large deformation (the Mogangling slope, the Xinhua slope and the Zhengjiaping slope) are selected to analyze the evolution process and the related potential failure mechanisms in the reservoir bank slopes.

4.1. Evolution of deformation in the reservoir bank slopes

4.1.1. The Mogangling slope

The Mogangling slope, with a trailing edge elevation of 1450 m and a leading edge elevation of 1110 m, has a length of 650 m, a width of 770 m, an average thickness of approximately 120 m and a volume of roughly $2.4 \times 10^6$ m$^3$. The Mogangling slope is located at the tail of the reservoir and is distributed along a NEE to SWW direction with a typical armchair-shaped terrain and a main sliding direction of S75°E (Figure 6(a)). This slope was formed after the 1786 Kangding earthquake as evidenced by its special topographic features and strong seismic intensity (Dai et al. 2006). This slope can be divided into four zones after the influence of the 1786 Kangding earthquake, including a trailing edge palisade, a collapse slope area, an accumulation area in the leading edge (the main sliding part) and an upstream debris flow area (Figure 6(a)). Figure 6(b) shows the typical geological section (Profile I-I) of the Mogangling slope. The accumulation area, exhibiting a gentle sloping angle at its leading edge, is developed in quartz diorite ($\delta_0^{23}$) and plagiogranite ($\gamma_0^{23}$) on the west side of the Dadu River fault, and its shallow layer presents a structure constituting block cracking and fragmentation under the effects of strong weathering and unloading. Meanwhile, a drill hole revealed that the constituent material of the slip zone has the same features with the main accumulation body except for fine-grained soil, as is common in general slip zones. The structure and evolution of the Mogangling slope display common features with lots of landslides triggered by the 2008 Wenchuan earthquake (Xu et al. 2009; Zhou et al. 2013).

Prior to impoundment, the Mogangling slope was detected as a source of danger due to its extensive influence on the powerhouse of the Shazui Hydropower Station, road conditions and human lives (Figure 6(a)). After impoundment, numerous collapses formed in response to the rising water near the water surface. To record the deformatonal trend, an automatic monitoring system for slope external deformation based on the global navigation satellite system (GNSS) was used to determine the value of surface deformation beginning in May 2015, for which Figure 6(a) shows the layout of the deformation monitoring site and its coordinate system. Taking the horizontal deformation data (where the horizontal plane is decided by X and Y) of monitoring points MP02 and MP04 as examples, the deformation process and velocity corresponding to the fluctuation of reservoir water levels are described in Figure 7. From these figures, it can be seen that the deformation is very small and the deformation velocity fluctuates within ±2 mm/d, which indicated the initial water storage and subsequent fluctuations of the water level (also including precipitation) generated small contributions to the deformation embodied solely within local collapses in the
slope toe. This slope maintains a good stability status, which is in accordance with the gentle slope angle at the leading edge (Figure 6(a)), the higher-strength and water-resistant material (i.e. large block cataclastic boulders), and the sliding zone lacking finer-grained material, which is comprised of higher-strength rock strata. These properties permit a better drainage capacity in order to maintain a constant pore water pressure and a better resistance to facilitate a decrease in the shear strength parameters on the sliding surface.

Figure 6. Geological map of the Mogangling slope: (a) overview of the Mogangling slope; and (b) geological cross-section (I-I) of the Mogangling slope.
4.1.2. The Xinhua slope

As shown in Figure 5, the Xinhua slope is located in the second zone of the reservoir and is characterized by a trailing edge elevation of 1420 m, a leading edge elevation of 1065 m, a length of 600 m, a width of 450 m, a thickness of approximately 50–70 m and a volume of approximately $7 \times 10^6$ m$^3$ (Figure 8(a)). The Xinhua slope is mainly composed of ancient landslide deposits that grew from the initial rock slope and were caused by adverse joints, gravity, and compression and crushing action. According to Figure 8(b), the typical geological section (Profile I-I) of the Xinhua slope demonstrates that the exposed bedrock is Triassic Baiguowan ($T_{3bg}$) sandstone and slate and greyish black mudstone, which are characteristic of lower strength. The composition of the material in the deposits is dark grey rubble soil (sand slate), and the contents of stone, crushed stone and soil (silt) are approximately 10%, 50% and 40%, respectively. Moreover, the slip zone is composed of a pebbly soil with lower permeability.

As a vulnerable slope with obvious failure phenomena near the location of the dam site, this slope poses a serious threat to the reservoir operation. The GNSS technology (Figure 8(a)) was also used to record the deformation beginning in May 2015.
As shown in Figure 9, some monitoring information about deformation and water level is recorded. The monitoring results indicate that no immediate deformation trend occurred during the early stage of rapid water storage. That is, the deformation of the Xinhua slope demonstrated a delayed response to the initial rapid rise of the water levels. It is inferred that the delayed effect depended upon the rock/soil permeability (Miao et al. 2014) and that the shear strength after immersion within the reservoir water was enough to resist the increasing shear stress, but the arrival of the rainy season directly led to large deformation due to the arrival of the rainy season combining with Figure 2(a). After July, the deformation appears increase sharply, and
the maximum deformation velocity reached approximately 182 mm/d. Meanwhile, as shown in Figure 9, fluctuations of the deformation velocity also had a close connection with the varying water level, but ultimately returned to a steady state. On the other hand, based on the phenomenon of tensile crack in the trailing edge and local collapse in the front and larger deformation value at higher elevation, the deformation process of the Xinhua slope can be regarded as retrogressive, that is the trailing edge experienced sliding followed by creep of the leading edge.

4.1.3. The Zhengjiaping slope

The Zhengjiaping slope is located in the second zone of the reservoir adjacent to the Xinhua slope (as shown in Figure 5). Due to the influence of the reservoir impoundment, sections of the provincial highway (S211, stretching from Luding County to Shimian County) below an elevation of 1130 m were submerged, as the rebuilding of highway S211 had been completed prior to impoundment. This slope is located just on the rebuilt portion of highway S211 between section K8 + 030 m and section K10 + 750 m (Figure 10(a)). It is developed within a Triassic Baiguowan (T3bg) thin, sandy shale stratum that is cut by the Dadu River fault (located in the slope toe), and it shows a counter-tilt layer rock slope, whose rock stratum is intersected with the

![Figure 9](image_url)

Figure 9. Relationship between deformation and water levels for the Xinhua slope: (a) deformation value and water fluctuations; and (b) deformation velocity and fluctuation velocity.
slope surface at a small angle with a steep dip within the interior of the slope as shown within the I-I cross-section in Figure 10(b). As a kind of counter-tilt layer rock slope with softer strength, toppling deformation in the sand shale stratum is easily formed under the effects of gravity and an incised valley and, therefore, causes numerous extrusion deformation cracks, the extent of which increases with an increase in the elevation and a decrease in the distance from the slope surface.
Simultaneously, severe unloading and weathering effects aggravate the phenomenon of rock fragmentation in the slope surface.

Some local collapses and cracks appeared during October 2015, and obvious deformation is located in a secondary landslide body located above highway S211, which is artificially disturbed due to the reconstruction of S211. To record the deformation, a GNSS system was installed in April 2016, as is shown in Figure 10(a), and the monitoring results of ZP01 and ZP03 are described as shown in Figure 11. The monitoring results indicate that the deformation is not sensitive to the water storage process or the fluctuations of the reservoir water level, and that this phenomenon infers that the reduction in shear strength within the fault and rock masses exists as a long-term evolutionary process. However, upon reaching a certain level, the decrease in the shear strength of the fault and rock masses in the slope toe results in more severe toppling deformation until April 2016 as shown in Figure 11(a). A rapid deformation velocity appeared during the period from 21 April 2016 to 7 June 2016, with an average value of 3.58 mm/d for monitoring point ZP01, and the total deformation reached an approximate half-meter grade. After that time, monitoring point ZP01 was inclined towards local instability with a greater deformation rate (approximately 28.5 mm/day) in 3 August 2016 (a new monitoring site was installed at the same location after the instability of ZP01). Obviously, the trailing cracks

![Figure 11. Relationship between deformation and water levels for the Zhengjiaping slope: (a) deformation value and water fluctuations; and (b) deformation velocity and fluctuation velocity.](image-url)
induced by large deformation and local collapses have a direct association with rain-
fall infiltration (as shown in Figure 2(a)) on the basis of long-term immersion and
excavation, and after rainy season, that is October, the deformation tends to a rela-
tively stable state, as described in Figure 11. On the other hand, the Zhengjiaping
slope also represents a retrogressive failure model as the product of the propagation
of tension cracks in the trailing slope and the accelerated toppling deformation
caused by the progressive degradation of shear strength in the slope toe.

4.2. Analysis of the mechanisms and potential failure mode

As mentioned above, reservoir impoundment, water fluctuations, rainfall infiltration
and external disturbances are the most important triggering factors for inducing the
deposition and failure of slopes, but further points must be clarified about the trig-
gering mechanisms, potential failure models and different responses that occur under
the same conditions. In this study, two major potential failure models, including a
creep–shear–tension failure model and a toppling–tensile–shear failure model, are
proposed to interpret the general evolution of larger-scale slopes in the
Dagangshan reservoir.

The reactivation of and large deformation mechanisms for accumulative landslides
have been received with widespread understanding and mainly include water soften-
ing, pore water pressure surging and seepage effects (Sun et al. 2009; Zhou et al.
2010, 2016). In the Dagangshan reservoir, this kind of landslide (i.e. an accumulative
landslide) accounts for a large percentage of events and results from being in a state
of creep for a long time, as is represented by the Xinhua slope and the Mogangling
slope. Figure 12(a) describes the evolutional mechanism for this type of slope in this
reservoir. As elaborated in the mechanism diagram, the initial shear stress can be cal-
culated using the slice method. After impoundment, the rising water will saturate the
leading edge of the slope to impose an increase in the pore water pressure, a reduc-
tion in the shear strength and an increase in the bulk density, which will deteriorate
the natural condition of the slope and create a newly distributed internal stress field,
following which the balance of the long-term creep process will be broken. In addi-
tion, fluctuations of the water level will accelerate deterioration, especially rapid var-
iations (Li et al. 2016) that induce a seepage traction force. The slope toe is initially
influenced, leading to a decrease in the shear strength and an increase in the shear
stress, which causes deformation and the shear strength to exceed the decreasing
peak shear strength ($\tau_p$) and decrease to the residual shear strength ($\tau_r$). As shown in
Figure 12(a), an overstressed zone exists in the slope toe (i.e. where the stress exceeds
the shear strength of the material), and this zone will propagate alone the sliding sur-
face, causing an accelerated creep. Simultaneously, during the process of deformation,
some tension cracks, including shallow and deep, are formed in the trailing edge due
to the effects of traction. Such a landslide will be globally unstable with shear destruct-
ion in the middle zone and tensile destruction at the trailing edge in the creep—
shear–tension fracture model.

Another model is described in Figure 12(b), which expresses the evolution of fail-
ure of a counter-tilt layer lithology with the characteristic of being sensitive to water
(e.g. softened rock or a well-developed weak interlayer and structural plane). The Zhengjiaping slope is one such type of slope. As a counter-tilt layer lithology composed of softer rock (i.e. a thin sand shale stratum), the Zhengjiaping slope has been in a state of bending creep under the effects of long-term gravity, which causes toppling deformation and broken rock masses, which are also associated with serious unloading and weathering. After a period of impoundment, the fault (f) and the thin sand shale are gradually infiltrated and softened, which reduces the shear strength of rocks/soil masses at the leading edge, resulting in more severe toppling deformation. Accordingly, the rebuilt highway S211 represents an artificial disturbance, which not only causes an increase in the shear stress, but forms a deformation-free surface.

Figure 12. Typical failure mechanisms and modes for landslides in the Dagangshan reservoir: (a) a creep–shear–tension failure model (such as the Mogangling slope and the Xinhua slope) and (b) a toppling–tensile–shear failure model (such as the Zhengjiaping slope).
Therefore, local deformation appears near highway S211 with all of these coupled effects, and an overstressed zone is formed that expands upward. On the other hand, some tension cracks, including shallow and deep, are formed under the effects of traction. In addition, seasonal precipitation easily penetrates the rock masses covered with a thin layer and profitably makes a contribution to the propagation and coalescence of the trailing cracks; therefore, large deformation is encountered during this time. Rainfall also presents serious influences on the decrease in the shear strength and the increase in the shear stress; therefore, an overstress zone will finally be formed at the trailing edge. Between the leading edge and the trailing edge, there is a ‘locking portion’ in the middle, and the slope will be globally unstable when the middle ‘locking portion’ fails under concentrated shear strength, and represents the toppling–tensile–shear failure model.

5. Discussions

In China, the Three Gorges has been regarded as a concentrated area of reservoir landslides. Accordingly, many reservoir landslides have been widely reported (Qi et al. 2006; Jian et al. 2009; Miao et al. 2014; Yin et al. 2016). However, since the development of numerous large-scale water conservancy projects in recent decades, and due to a complex geological environment, the safety from reservoir landslides in south-west China is also prominent, such as for the Maoergai reservoir in the Heishui River and the Jinping-I reservoir in the Yalong River, although corresponding reports are comparatively vacant. In this area, with characteristically deep and narrow valleys, active tectonism (e.g. earthquakes) and intense unloading and weathering effects cause the breakage of rock masses, especially within shallow layers, widespread loose Quaternary sediments, well-developed weak interlayers and structural planes. Meanwhile, the physical and mechanical properties of rock/soil materials are easily affected by water, especially with regard to water storage and sudden drawdowns. Simultaneously, more severe deterioration will occur when these effects are coupled with rainfall or external disturbances, such as the 2008 Wenchuan earthquake in the Sichuan Province, south-west China, which directly caused landslides and led to additional fractured rock masses and loosened deposits (Zhou et al. 2013). This suggests that both engineering and non-engineering measures should be made to prevent the effects of reservoir landslides, including slope reinforcement, migration, reasonable selection of highway routes to avoid instability slope, reasonable reservoir operation schemes, warning systems and forecasting catastrophic landslides.

Correspondingly, the extent of the development and distribution of landslides in the Dagangshan reservoir is not very prominent relative to other reservoirs in south-west China, such as the Maoergai reservoir (Zhou et al. 2017) and the Jinping-I reservoir. Form the viewpoint of reservoir operation, the reservoir water level variation has some close relationship with the development of reservoir landslide (Xia et al. 2015). The Dagangshan reservoir is a daily regulation reservoir, the total storage capacity of which is $7.47 \times 10^8$ m$^3$ with a regulating storage capacity of $1.17 \times 10^8$ m$^3$, so the regulating storage ratio is approximately 16%, which is a relatively smaller value than that of the Moergai (82.8%) and Jinping-I (63.3%) reservoirs. Moreover, the
designed water level of this reservoir fluctuates within a range of 10 m, although the maximum daily fluctuation of the water level to date has reached approximately 3.39 m/day, and most of the amplitude of the water fluctuation is mainly concentrated between 0.15 m/day and 0.4 m/day, which indicates that the development of landslides that are affected by water fluctuations is relatively small in the Dagangshan reservoir (as shown in Figure 13). Therefore, a preliminary conclusion is considered that except for the influence of geological conditions, the reservoir operation is also closely associated with the extent and amount of the development of reservoir landslides.

6. Conclusions

After impoundment, numerous landslides have been found continually along the banks of the Dagangshan reservoir, which mainly include shallow slides in Quaternary accumulative layers or fracture rock masses with severe unloading and weathering. These also include seven unstable deformation slopes that can be classified into accumulative landslides and softened rock landslides that present failure phenomena for local collapses near the water surface and tensile cracks in the trailing edges of the slopes, which are induced by large deformation, as well as the characteristics of evolutionary failure tendencies from shallow slides to deep-seated slides resulting from long creep histories. As a whole, the landslides that have occurred in the Dagangshan reservoir are associated with reservoir water levels and precipitation directly or indirectly from the perspective of their temporal distribution. Meanwhile, manmade disturbances also play a crucial role in the development of landslides. Spatially, these landslides are mainly distributed in the reservoir tail and middle, are presented within a linear distribution along the Dadu River fault and the Moxi fault.
with large seismic belts and are mainly developed within deposits and softened rocks, which are sensitive to water.

Three typical slopes with deformation patterns are selected to exhibit the deformation and failure processes of the reservoir bank slopes in the Dagangshan reservoir, which indicate that the initial water storage and subsequent fluctuations of the water level (including precipitation) made small contributions to the Mogangling slope due to better rock lithologies and drainage capacity within the sliding zone. However, the Xinhua slope and the Zhengjiaping slope present large deformation, local collapses and tension cracks under the direct effects of rainfall infiltration on the basis of the long-term influences of reservoir water levels (manmade disturbances are also included). Moreover, based on the recognition of the deformational and failure processes of the typical slopes, two types of failure models are proposed to interpret the failure mechanisms of the deformation slopes in the Dagangshan reservoir, including a creep–shear–tension failure model and a toppling–tensile–shear failure model.

The extent of the development and distribution of reservoir landslides in the Dagangshan reservoir is not prominent relative to the Maoergai or Jinping-I reservoirs of south-west China. A comparative analysis of reservoir operations is presented, which preliminarily infers that in addition to the effects of geological conditions, smaller-scale fluctuating water levels are important external factors influencing the non-significant development of landslides in the Dagangshan reservoir.

Disclosure statement

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