

Potential for a Ganhaizi landslide-generated surge in Xiluodu Reservoir, Jinsha River, China

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Received: 27 February 2014 / Accepted: 14 August 2014 / Published online: 24 August 2014
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Abstract Xiluodu hydropower station is located on the Jinsha River, the upper course of the Yangtze River, and is the third largest hydropower station in the world. In May 2013, impoundment of the Xiluodu Reservoir started and preliminarily operation began, and the reservoir area was subject to frequent landslides and collapses. On 23rd July 2013, Huangping landslide, with a volume of $20 \times 10^4 \text{ m}^3$, slid into the Xiluodu Reservoir and generated an impulse water wave that killed 12 people on the opposite bank. The reservoir water level will fluctuate by 60 m each year, between the elevations of 540 and 600 m, so any impulse wave generated by a landslide in the reservoir is a major concern in the preliminary impoundment phase. Ganhaizi landslide is the biggest landslide in Xiluodu Reservoir, with a volume of about $7,800 \times 10^4 \text{ m}^3$. This landslide is only 14 km upstream from the Xiluodu Dam. In particular, the landslide deformation has obviously intensified after impounding. This paper analyzes the terrain and deformation features of Ganhaizi landslide, and we propose that sliding on the Ganhaizi slope may occur at the front part of the landslide. The front part of landslide has a volume of around $300 \times 10^4 \text{ m}^3$; the elevation of the barycenter of this part is 510 m. The sliding mass is thus largely

underwater, and can pose a threat mainly in the form of surges. Based on the underwater landslide terrain in the mountain reservoir area, the authors have modified the seabed landslide-generated surge source model of Grilli and Watts (2005) to form an initial source model for an underwater landslide-generated surge. Using this model, the authors predicted possible surge disasters that can be caused by a Ganhaizi landslide at both the dead water level of 540 m and the normal water level of 600 m in Xiluodu Reservoir. The surge disaster might mainly strike the area within 5 km along the river channel both upstream and downstream of the landslide area, but generally poses no threat to Xiluodu Dam. This paper aims to provide technical support for the safety of Xiluodu Dam and the reservoir area. The newly established underwater landslide-generated surge initial source model for mountain reservoir areas may serve as reference for calculation of underwater landslide in other reservoir areas around the world.

Keywords Xiluodu · Reservoir · Ganhaizi landslide · Underwater landslide · Impulse wave source model

Introduction

Water impoundment in reservoirs is commonly a key factor inducing slope collapses and landslides, so reservoir areas may be subject to frequent landslide-generated surges (Huang 2014). The study of landslide-generated surges in reservoirs is thus important for the safety of the reservoir areas. Ataie-Ashtiani (2007, 2012) studied the generation, spread and run-up of surges for several landslides in Shafa-Roud Reservoir using LS3D and FUNWAVE Boussinesq equations, while utilizing related empirical, experimental and theoretical formulae to compare the height and speed

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of waves for analysis. Walder (2003, 2006) established a mathematic model for underwater landslide-generated surge sources for several rock and soil movement types using physical similar tests and the boundary element method, and validated the method using the surge event induced by a volcanic debris flow in Washington Swift Reservoir in America in 1980, proving it effective. Akgün (2011) used an empirical formula to predict and evaluate impulse waves generated by the Hardisagir landslide in Kurtun Dam Reservoir in North Turkey. Crosta et al. (2013) used the 2D FEM and Navier-Stokes equations to analyze the Vajont landslide-generated surge.

During the preliminary operation stage of a reservoir, the reservoir area may be subject to frequent landslides and collapses that can trigger impulse waves. For example, in June 2003, the Three Gorges Reservoir started impoundment, and on July 14, 2003, a landslide occurred in Qianjiangping, Zhigui County of Hubei Province, generating a surge that caused 12 deaths (Wang et al. 2004). In February 1960, Vajont Reservoir in Italy started impoundment, and on October 9, 1963, a giant landslide occurred on the slope near the dam on the left bank (Müller 1964). The landslide caused over $20.5 \times 10^6 \text{ m}^3$ water to overtop the dam (Bosa and Petti 2013), while the landslide-generated surge destroyed several villages and towns downstream and resulted in 1,925 deaths. All these landslide disasters in reservoir areas around the world suggest that at the preliminary operation stage of reservoirs, studies of potential landslide-generated surges should be carried out to protect the safety of people in the reservoir areas.

Along Jinsha River, which is the upper course of the Yangtze River in China, cascade hydropower stations (including Xiluodu Hydropower Station) are under construction. Since reservoir impoundment began in May 2013, deformation of Ganhaizi landslide near the dam site of Xiluodu Reservoir has intensified, and potential failure of the slope may cause a significant disaster. This paper will examine the disasters that may be caused by surges generated by Ganhaizi landslide in the Xiluodu Reservoir area, while modifying the calculation model of underwater landslide-generated surges, to provide a scientific basis for risk management of the Ganhaizi landslide, as well as a reference for calculation of underwater landslide-generated surges in other mountain reservoir regions of the world.

Characteristics of Xiluodu Reservoir and Ganhaizi landslide

Xiluodu Hydropower Station is located in the Xiluodu Canyon of Jinsha River at the junction of Leibo County in Sichuan Province and Yongshan County in Yunnan Province, in the transitional belt between the Qinghai-Tibetan Plateau, Yunnan-Guizhou Plateau and Sichuan Basin.

Xiluodu Hydropower Station is the largest of four giant hydropower stations under construction in the downstream Jinsha River. In August 2003, preparation for construction of the station was started; in November 2005, construction began; in November 2007, water impoundment behind Xiluodu Dam began. In May 2013, the first generators at Xiluodu Hydropower Station began producing electricity. According to the project plan and schedule, in 2015, the project will be completed. On the left and right banks of the power station, there are underground generators with the total installed capacity reaching 13.86 million kW, second only to the Three Gorges Hydropower Station in China and Itaipu Power Station jointly constructed by Brazil and Paraguay. Located at the north side of Yongshan County, Xiluodu Dam is a concrete arch dam, with a dam crest elevation of 610 m, a maximum dam height of 285.5 m, and a dam crest arc length of 698.07 m. The normal impoundment water level in Xiluodu Reservoir is 600 m; the dead water level is 540 m; the total capacity is 12.8 billion m^3 , subject to annual operating fluctuations. The reservoir has a high and middle canyon channel, with a backwater length of 204 km; submergence of the reservoir involves nine counties in Sichuan and Yunnan Provinces. According to geological surveys and relevant data, 81 landslides and collapses have developed in the Xiluodu Reservoir area, with an estimated total volume of around $16.46 \times 10^8 \text{ m}^3$ (Deng and Wang 2011). After impoundment of Xiluodu Reservoir, deformation of some slump masses has appeared, of which Ganhaizi landslide is the nearest to the dam site and the biggest.

Ganhaizi landslide is located on the right bank of Jinsha River, and is about 14 km above the Xiluodu Dam site (Fig. 1, right map). The bank slope is in a deep valley at the concave bank of Jinsha River, where the water level in Jinsha River in dry seasons is around 384 m and the riverbed elevation is around 365 m. Ganhaizi landslide has alternating steep and gentle topographic features. The slope above the elevation of 950 m has bedrock exposed and is steep—about 1,000 m high with partial cliffs. Between the elevations of 600 and 950 m, the slope is gentle, with an average slope of 17° . At this section, there are two large platforms developed, i.e. Ganhaizi Platform and Tangjiawan Platform; between the two platforms is a slope of 42° . Ganhaizi Platform has an elevation of 640–650 m; Tangjiawan Platform has an elevation of around 880–900 m. The slope below the elevation of 530 m is a gentle slope of about 21° . The slope below the elevation of 950 m was mainly an accumulation zone for deposits of Quaternary age.

Structurally, the slope lies near the anticline crest of the Shitan. The anticline stretches about 40° along Jinsha River and is about 10 km long. The rock stratum dipping direction is 100° – 130° with its dipping angle of 10° – 15° . The exposed bedrock consists of thick-massive biocalcarenite,

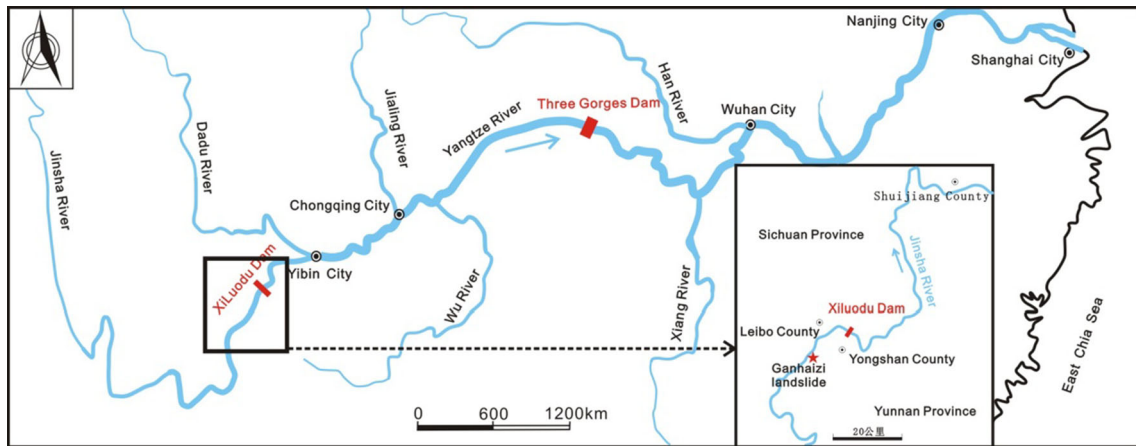


Fig. 1 Location map of Ganhaizai landslide and Xiluodu Dam. Jinsha River is the upper course of the Yangtze River, and Xiluodu Dam is one of biggest dams in the Jinsha River

Fig. 2 Geological map of Ganhaizai landslide. The *black line* is the boundary of the bedrock strata; the *green dotted-line* is the boundary of the Quaternary sediments. The *red dashed line* is the boundary of the Ganhaizai landslide; the *straight red line* is the cross-section line. The *hachured line* is the potential failure zone. The *upper right photo*, taken in Nov. 13, 2013, shows the fissure in the slope

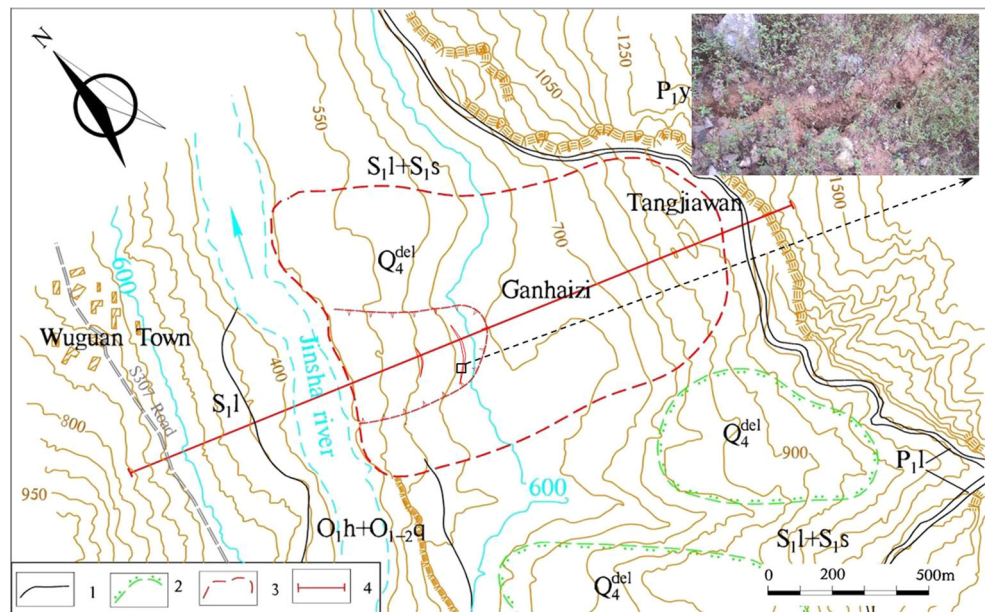
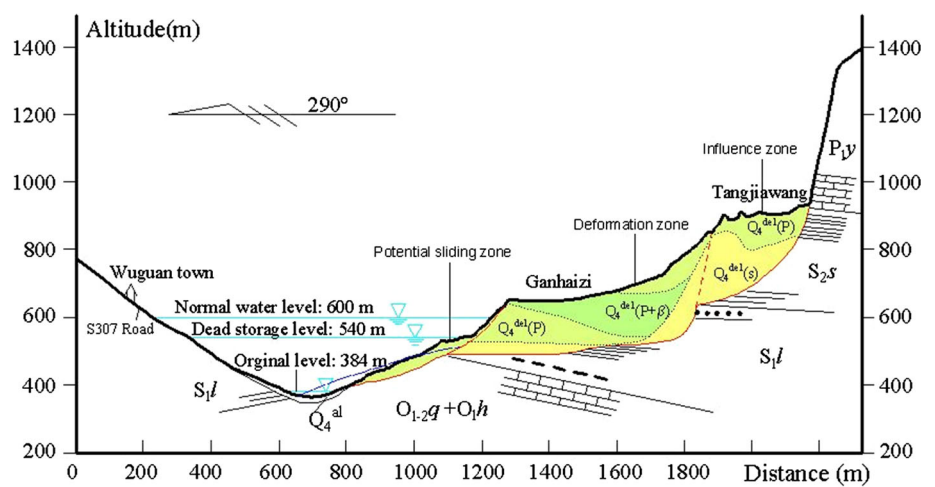


Fig. 3 Engineering geological section map of Ganhaizai landslide. The *red line* is the location of the sliding surface; the *red dashed line* is the location of the secondary divided zone. Front potential sliding zone, middle deformation zone and back influence zone are also divided. The *blue dashed line* marks the possible surface after sliding in the future (after CHIDI 2009)



argillaceous banded limestone and ferrous argillaceous limestone from the Qiaojia Group (O_{1-2q}) in the Ordovician, argillaceous shale with siltstone from Longmaxi Group (S_{1l}) in the Silurian, sand-mudstone with limestone from Shimenkan Group (S_{2s}) and sand-mudstone from Liangshan Group (P_{1l}), Yangxin limestone (P_{1y}) and Emeishan basalt ($P_{2\beta}$) of the Permian (Fig. 2). Field investigations indicate (Fig. 3) that the Quaternary age deposits mainly consist of gravel soils, in which $Q_4^{del}(P)$ is gravel soil mainly composed of Yangxin limestone (P_{1y}) gravels, $Q_4^{del}(P+\beta)$ is gravel soil composed of mixed Yangxin limestone (P_{1y}) and basalt ($P_{2\beta}$) from the Permian, and $Q_4^{del}(S)$ is gravel soil mainly composed of rocks from the Silurian (Zou and Zhang 2011; Fan and Wang 2013).

In terms of landform, Ganhaizi landslide features a steep cliff at the back edge, while its front edge reaches the alluvial flat of Jinsha River. The south boundary of Ganhaizi landslide is near a ridge upstream of Ganhaizi, while the north boundary is a ridge downstream of Ganhaizi. Ganhaizi landslide extends about 620 m along the river, with a profile length of 1,500 m and average thickness of 160 m (the average thickness of the front part is about 25 m); the sliding direction is around 290° – 300° . The total volume of the landslide is about $7,800 \times 10^4 \text{ m}^3$ (Zou and Zang 2011).

Based on the historical cracking deformation and the landform characteristics, Ganhaizi landslide can be divided into a front potential sliding zone, a middle deformation zone and a back influence zone (Fig. 3). Due to the fast flow and strong erosion by the Jinsha River, the front edge of the Ganhaizi Slope is subject to continuous erosion, having caused bank collapse and influenced the stability of the landslide. Lan et al. (2001), Li et al. (2012), CHIDI (2009), Zou and Zang (2011), Deng and Wang (2011) and Fan and Wang (2013) had carried out special studies on the evolutionary process, deformation and stability of Ganhaizi landslide respectively, and all concluded that the Ganhaizi middle deformation zone and Tangjiawan back influence zone were relatively stable, with a factor of safety (FOS) exceeding one for several reservoir water levels and earthquake conditions, while the front zone has relatively poor stability. After the first phase of impoundment in Xiluodu Reservoir started from May 4, 2013, large tension fissures appeared at the back edge of the front zone; one group of fissures trended parallel with the river and stretched nearly 100 m, with a width of around 30–50 cm and a vertical offset of around 30 cm. The phenomenon and the previous studies show that the front zone is an unstable area of Ganhaizi landslide. The slump mass of the front zone delineated by the last arc fissure is about 300 m long along the river, with a profile length of about 400 m; the

average thickness is about 25 m; the greatest thickness is 45 m; and the volume is about $300 \times 10^4 \text{ m}^3$ (Fig. 2).

If the front sliding zone fails, the mass will run out. It is difficult to predict the landslide movement. In mountain reservoir, some landslides could run to the opposite bank slope with some distance (Zhuang 2013); some landslides only run a little distance, cannot reach the toe (Igwe et al. 2014). Supposed the mass reach to the bottom of the riverbed, the dynamic character value of the landslide is easy to estimate and the estimated value will be not too large or too small. Based on geological engineering analogy, the landform after failure was analyzed. As shown in Fig. 3, the blue dotted-line refers to landform after sliding with the slope angle of 17° ; the barycenter after sliding is 435 m; the sliding drop is 75 m; and the sliding distance is 210 m.

With implementation of a relocation program in Xiluodu Reservoir area, the former residents on Ganhaizi landslide have moved; on the land, oranges and crops have been grown (Fig. 4). A residential area nearby is Wuguan Town on the opposite bank, which is located at an elevation of 620–710 m. If $300 \times 10^4 \text{ m}^3$ rock and soil mass of Ganhaizi landslide slides, few structures would be endangered on the slide area, but it may create surges in the reservoir. The scope and degree of potential surge-caused damage have not been specially considered in previous studies, and are still to be evaluated.

Ganhaizi landslide-generated surge calculation model

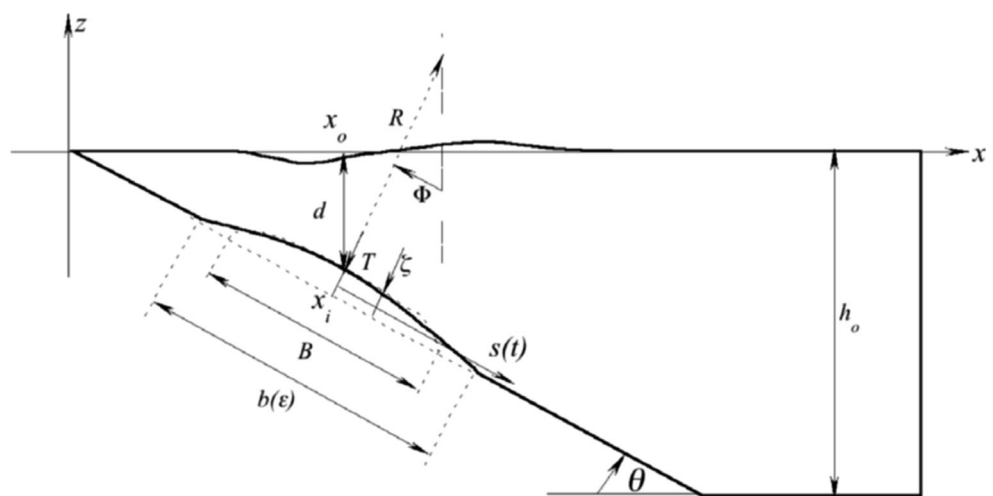
The barycenter of the sliding area of Ganhaizi landslide has an elevation of 510 m; thus no matter whether the reservoir is at the 540 m dead water level or at the 600 m normal impoundment level, the barycenter of the potential sliding zone is underwater. After impoundment in the reservoir, the part exposed above the water level is less than 10 % of the total vertical length of the slope. Therefore, surges generated by Ganhaizi landslide would be substantially caused by an underwater landslide.

More number of studies on geological disasters generated by underwater landslides in reservoirs, as well as submarine landslides are carried out much (Prior 1984; Norwegian Geotechnical Institute 2005; Vanneste 2011). In this paper, achievements made in submarine studies carried out by Grilli and Watts (2005), Enet et al. (2003), and Enet and Grilli (2007) and others on tsunamis and GEOWAVE models are used for reference and improved to establish a model for calculating surges generated by the Ganhaizi landslide. A sliding movement model of a rigid mass (Fig. 5) was established by Grilli and Watts (2005). Based on moment equilibrium, plus gravity, hydraulic drag force and buoyancy, the movement of the rigid masses is described mathematically as follows.



Fig. 4 The deformation band of front zone and the road and town threatened. The picture was taken on Nov. 13, 2013, when the water level in Xiluodu Reservoir was 540 m

Fig. 5 Grilli and Watts (2005) 2D submarine landslide tsunami model. The sliding movement of a rigid mass is modeled as a symmetrical semi-ellipse sliding block, whose length along the long axis is B and T at the thickest point



The initial acceleration and final speed are:

$$a_0 = \frac{g \sin \theta (\gamma - 1)}{\gamma + 1} \tag{1}$$

and

$$u_t = \sqrt{0.5gB\pi \sin \theta (\gamma - 1)} \tag{2}$$

The sliding displacement and time are:

$$s(t) = s_0 \ln \left(\cosh \left(\frac{t}{t_0} \right) \right), \tag{3}$$

$$s_0 = u_t^2 / a_0, \tag{4}$$

$$t_0 = u_t / a_0. \tag{5}$$

The original characteristic tsunami amplitude in the time of t_0 is:

$$\eta_0 = 0.853 \cdot s_0 (0.04772 - 0.03559 \sin \theta + 0.00813 \sin^2 \theta) \times \left(\frac{T}{B} \right) \left(\frac{B \sin \theta}{d} \right)^{1.25} \left(1 - e^{-2.2027(\gamma-1)} \right) \tag{6}$$

The original characteristic tsunami wavelength is:

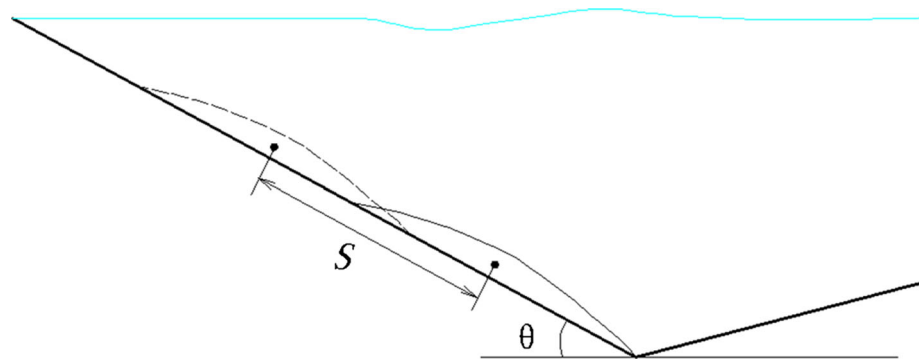
$$\lambda = t_0 \sqrt{gd} \tag{7}$$

The position of the trough of the original characteristic tsunami is decided by:

$$X_{min} = 0.95 \left(\left(\frac{d + \frac{T}{\cos \theta}}{\tan \theta} \right) + 0.4338s_0 \cos \theta \right) - \left(\frac{d + \frac{T}{\cos \theta}}{\tan \theta} \right) \tag{8}$$

where $\gamma = \rho_s / \rho_w$; ρ_s refers to the density of the slump mass; ρ_w refers to the density of water; and g refers to the acceleration of gravity. a_0 is the initial acceleration of the slide, and u_t is the terminal velocity, s_0 is the sliding distance, t_0 is the character travel time of the slide. λ is tsunami wavelength and X_{min} is the trough position from the sliding bank. θ , d , B and T is the geometer parameter of the slope and sliding block as shown in Fig. 5 through obtaining a_0 and u_t , s_0 can be obtained, and further the

Fig. 6 Concept model of underwater landslides in mountainous areas



initial surge wave height and the initial surge source can be obtained.

In the underwater landslide model, the landslide movement is related only to θ , B and ρ_s . This model is applicable when the sliding landform follows a uniform slope of θ , and when the shape of the landslide mass does not change as it slides. However, the slopes in mountain areas, particularly the mountain areas in the southwestern canyons of China, are not long and uniform as are many submarine slopes and the slopes do not conform to the above-mentioned conceptual model. The landslide movement in mountainous areas generally has to stop when reaching the valley bottom (Fig. 6). To make the submarine landslide-generated tsunami source model of Grilli and Watts (2005) applicable to the underwater landslide in the mountain reservoir area, the landslide movement model must be modified.

Through comparison between Figs. 5 and 6, it can be seen that the greatest difference is the sliding distance. In Fig. 5, the slide distance is determined by θ , B and ρ_s , and generally the distance is very long. In Fig. 6, the slide distance is obviously affected by the topography of the valley, and the greatest distance is S . Therefore, the submarine landslide-generated surge source model of Grilli and Watts (2005) and Watts et al. (2005) needs to be modified at s_0 .

In the condition of underwater, there will be smaller dynamic friction than in the subaerial, and this friction of mountain landslide will be larger than that of submarine landslide. But the dynamic character of landslide is not easy to predict. In order to make the analysis on the safe side, the modified model does not consider the sliding resistance along slip surface just as same as the original model of Grilli and Watts (2005).

When underwater landslides occur in a mountain reservoir, the sliding distance can be estimated to be S , based on the landform characteristics of the landslide. In the equation, $s_0 = S$ is directly given. Through Eq. (1), a_0 can be obtained; through Eq. (4), we get $u_t = \sqrt{s_0 a_0}$, and then we can obtain u_t . Afterwards, we can use u_t obtained to calculate t_0 as shown in Eq. (5). When all parameters for

the underwater landslide movement are obtained, we can continue to use the initial surge source formula of Grilli and Watts (2005) for calculation. Through such modification, the calculation of the underwater landslide movement in the mountainous area will be more consistent with the practical conditions.

The source model code for submarine landslide-generated surges in the original Geowave program was modified based on the foregoing equations to form the initial surge source model for underwater landslides in the mountain reservoir. The Geowave models were established for two conditions, i.e. at water levels of 540 and 600 m; the calculation model is for the same region of about 23 km long and 21 km wide. In the calculation model, about a 40 km-long channel of Jinsha River is included; the channel is crooked and narrow with many tributaries. Within the range of calculation, towns involved on the riverbanks include Wuguan Town and Qianwanguan Town.

Using the 540 m water level as an example, the basic conditions of Ganhaizi landslide are respectively put into the calculation equations before and after modification. Figure 7 shows the form and location of the two initial surge sources. The initial surge source (Fig. 7a) is completely the trough that lies aside the opposite bank, and the trough amplitude is -40.3 m; in the Fig. 7b surge source, the trough is at the river bank near the landslide, and the trough amplitude is -22.2 m; in the front of the trough is the wave crest with the amplitude of 5.8 m; it is an initial surge field for a normal and complete underwater landslide. The difference between a and b is because in the model of an original submarine landslide-generated tsunami source model in Geowave, there is no landform control in the sliding movement; in the original model, the calculated landslide sliding distance is 897.5 m, and the greatest sliding speed is 53.4 m/s, while in the new model the sliding distance is 210 m, and the sliding speed is 17.2 m/s. The sliding distance without modification causes the surge location to be misplaced and the surge values are exaggerated. After modification, the form of the original surge obtained appears more reasonable, and character dynamic value calculated appears more confirm with the reality.

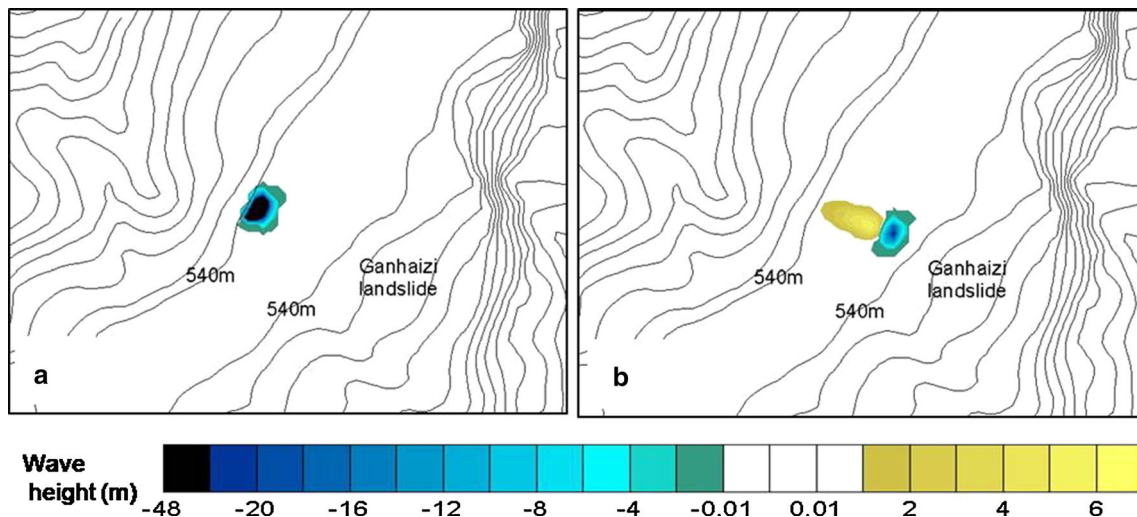


Fig. 7 The initial surge source form and location plan in GEOWAVE calculation before and after modification below the water level of 540 m. **a** Initial surge source form and location plan in GEOWAVE

calculation without modification; the surge sources are all negative waves. **b** Initial surge source form and location plan in GEOWAVE calculation with modification

Table 1 Input parameters and initial surge characteristic values

Input parameters	Water level		Original tsunami source characters	Water level	
	540 m	600 m		540 m	600 m
Barycenter depth (m)	30 m	90 m	Initial acceleration (m/s^2)	1.38	1.38
Incline angle	21°	–	Terminal velocity (m/s)	25.8	25.8
Landslide length	400 m	–	Trough amplitude (m)	–22.2	–4.8
Landslide width	300 m	–	Peak amplitude (m)	5.8	1.4
Maximum thickness	45 m	–	Tsunami wave length (m)	321.3	556.5
Landslide density	2,350 kg/m^3	–	Tsunami periods (s)	18.7	18.7

Parameters of Ganhaizi landslide at the water levels of 540 and 600 m are, respectively, put into the initial underwater landslide-generated surge source model for the mountain reservoir areas to calculate the initial landslide-generated surge source. For characteristic values of the parameters and the initial surge sources, see Table 1. 10,000 steps were set when the impulse wave was propagating; the actual time is about 1.2 h.

Predication and evaluation of tsunami disasters caused by Ganhaizi landslide

The GEOWAVE submarine landslide model has been used in many submarine landslide cases around the world; it is precise by comparison with the prototype results and test results (Enet et al. 2003; Enet and Grilli 2007). Therefore, the results obtained for submarine landslide-generated surges are reasonable and precise. The authors have only modified the code for the distance of landslide movement to make the landslide movement more consistent with the landform characteristics of the mountain reservoir. Therefore, the initial underwater landslide-generated surge

source model for the mountain reservoir area after modification should be as reasonable and precise as Geowave.

Through calculation, the surges generated by an underwater landslide of Ganhaizi at the 540 m dead water level and 600 m normal water level are obtained. At the water level of 540 m, the greatest surge amplitude generated in 30.4 s after occurrence of the landslide is 11.8 m, and appears near the central line of the channel (Fig. 8). The landslide shore run-up is 5.3 m. 55.4 s later, the greatest surge reaches the opposite bank, generating a run-up of 10 m. 39.9 s after occurrence of landslide, the surge reaches Wuguan Town, while the greatest surge in the channel is 2.5 m and the highest run-up is 4.8 m. 827 s later, the surge reaches Xiluodu Dam, with the greatest surge height of 0.045 m. 918 s later, the surge reaches Qianwangan Township, with the greatest surge height of 0.10 m. The average wave speed of the surge generated is 16.2 m/s.

As China has no surge warning regulations for domestic river channels, the tsunami warning plan issued by the State Oceanic Administration of the People’s Republic of China is applied, i.e. warning blue for 0–1 m, warning yellow for 1–2 m, warning orange for 2–3 m and warning

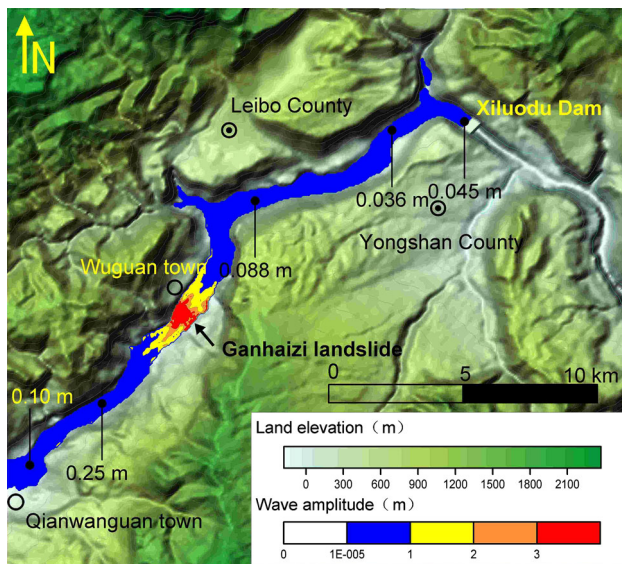


Fig. 8 The maximum amplitude and surge warning class in the channel at the water level of 540 m. In the figure, the elevation of 0 m is actually the elevation a.s.l. of 540 m; the area with an amplitude of above 0.5 m mainly lies within 7 km of the Ganhaizi landslide

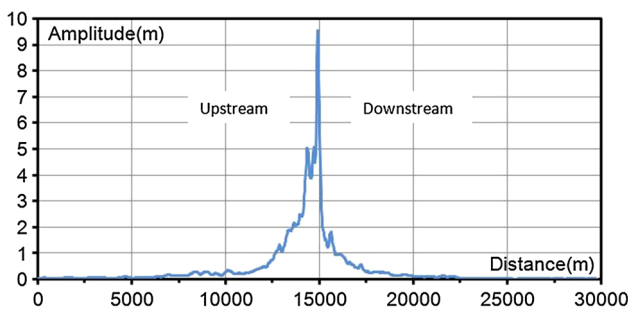


Fig. 9 Sectional view of the maximum amplitude of talweg at the water level of 540 m. The amplitude terminates at Qianwangan Township upstream and Xiluodu Dam downstream, with a total length of about 30 km. The figure generally reflects changes of surge amplitudes in the channel

red for above 3 m. Based on this warning plan, Fig. 8 shows that the red surge warning area is mainly near Ganhaizi landslide, over a 1.2 km length along the river. The orange surge warning area is within 950 m upstream and downstream of the red surge warning area. The yellow surge warning area is within 950 m upstream and downstream of the orange surge warning area. Generally, the river channel reach with the greatest amplitude of over 0.5 m runs 7 km long; and the channel reach with a yellow or higher warning run 5 km long.

As shown in the maximum amplitude sectional view of the talweg in the channel at the water level of 540 m (Fig. 9), the upstream channel within the red warning area is obviously longer than the downstream channel, with

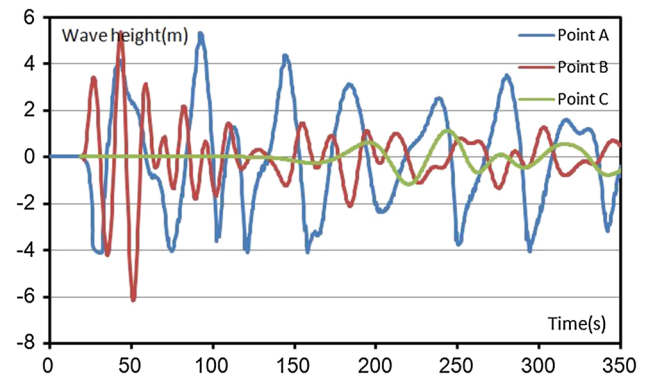


Fig. 10 The wave height process lines of three typical water particles. *Point A* is at the trough area of the initial surge source; *Point B* is at the peak area of the initial surge source; *Point C* is far away from the initial surge source area, which is located at the downstream of Wuguan Township

different decay rates. At the upstream of the red warning area, the maximum decay rate is 13.9 %, i.e. the amplitude decays by 13.9 m in 100 m, and the minimum decay rate is 1.13 %. In the orange warning area, the maximum and minimum decay rates are 1.16 and 0.31 % respectively. Generally, the amplitude decay along the channel is uneven.

With respect to initial wave form and movement, surges generated by underwater landslides have different characteristics to those generated by subaerial landslides. The subaerial landslide-generated surges are formed by interactions between water, solids and gases, with strong movement triggered by the impact effect; thus the initial surge form features a crescent-shaped high and a large peak. In the movement side, the initial water peak is the main source of movement, which advances to form the maximum wave heights at the various points along the river channel. Underwater landslide-generated surges are formed by interactions between solids and water, with movement of the water body triggered by the underwater solid movement; thus the form of the initial surge features a large trough but a small and long peak (Fig. 7b). In the movement side, the trough forms the biggest peak, and then advances outwards; the trough is the major source of movement. This can also be seen from the water wave process, in which the peak first appears in the formation area, with the maximum trough amplitude greater than the maximum peak amplitude (Fig. 10 Point B). In addition, at other points in the formation area and all points in the spreading area, a trough first appears, and then a peak appears (Fig. 10, Points A and C).

At the water level of 600 m, the maximum surge amplitude is generated in 26.3 s after the occurrence of the landslide and is 3.6 m, at the landslide bank side of the channel central line (Fig. 11). 63.6 s later, the maximum

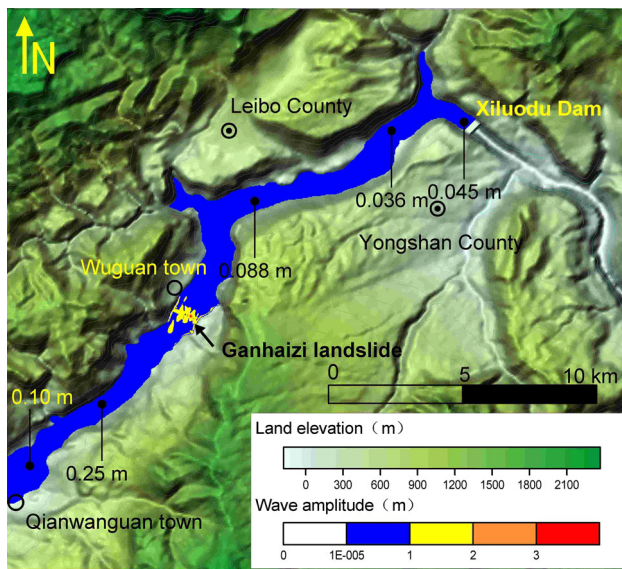


Fig. 11 The maximum amplitude and surge warning class in the river channel at a water level of 600 m. In the figure, the elevation of 0 m is actually the elevation a.s.l. of 600 m; river channel with the amplitude of above 0.5 m is 3 km long

surge moves to the opposite bank, with the maximum surge in the channel of 0.6 m and maximum run-up 1.8 m. 70 s later, the surge reaches Wuguan Town, with the maximum surge in the channel reaching 1.0 m and the maximum run-up reaching 1.5 m. 508 s later, the surge reaches the Xiluodu Dam, with a maximum surge height of 0.006 m. The red and orange surge warning area lies mainly along the channel center of Ganhaizi landslide, extending about 100 m along the river. The yellow warning area extends 1.5 km, which is outside of the orange warning area. Generally, the channel reach with a maximum amplitude of above 0.5 m is about 3 km long; and the channel with a yellow or higher warning level is about 2 km long.

At the water level of 540 m, the maximum surge elevation is 551.8 m and the run-up wave elevation reaches 550 m; at the water level of 600 m, the maximum surge elevation is 603.6 m and the run-up wave elevation reaches 601.8 m. At Wuguan Town and Provincial Highway S107, the minimum elevation is 620 m. Therefore, in terms of surge disaster prediction and evaluation, Ganhaizi underwater landslide-generated surges are unlikely to strike Wuguan Town and S107. For these two reservoir levels, surges will reach Xiluodu Dam with a maximum amplitude of several centimeters, and will generally not cause damage to nearby hydraulic structures. So the surges generated by an underwater landslide of Ganhaizi will mainly affect the 5 km channel upstream and downstream of Ganhaizi landslide, the two docks of Ganhaizi and Wuguan Town, riverside workers and aquaculture.

Before failure of Qianjiangping landslide in the Three Gorges Reservoir in 2003, the local government warned the

residents in the landslide area to move out, but failed to warn about surges, resulting in 12 deaths due to surges outside the landslide area. Therefore, when deformation of Ganhaizi landslide intensifies and a red landslide warning is given, warning of surges in the river channel should also be given. Vessels and residents along the banks within 5 km of the channel will receive the warning.

Conclusions

Based on the historical data and deformation, potential disasters caused by Ganhaizi landslide-generated surges have been studied, and the following conclusions can be drawn.

1. Ganhaizi landslide lies on the right bank of Jinsha River; it is about 14 km from Xiluodu Dam, and has a total volume of about $7,800 \times 10^4 \text{ m}^3$. Ganhaizi landslide can be divided into a front potential sliding zone, a middle deformation zone and a back influence zone. Based on the latest deformation after impoundment in 2013, a potential unstable area with the volume of $300 \times 10^4 \text{ m}^3$ is delineated.
2. Based on the characteristics of the underwater landslides in the western mountain-canyon reservoirs in China, the submarine landslide movement model of Grilli and Watts (2005) was modified to provide a source model more suitable for an initial underwater landslide-generated surge in mountain reservoir areas.
3. Surges caused by the instability zone of Ganhaizi landslide at reservoir levels of 540 and 600 m are predicted and calculated. For the water level of 540 m, the maximum surge height is 11.7 m, and channel reach with a wave height of above 1 m is 5 km long; for the water level of 600 m, the maximum surge height is 3.6 m, and channel reach with a wave height of above 1 m is 2 km long.
4. In terms of disasters caused by surges, surges generated by an underwater landslide of Ganhaizi would mainly affect the 5 km channel upstream and downstream of Ganhaizi landslide, the two docks of Ganhaizi and Wuguan Town, and riverside workers and aquaculture. It would unlikely cause any harm to Xiluodu Dam and nearby hydraulic structures.
5. This paper has studied disasters caused by impulse wave generated by landslide closest to Xiluodu Dam, to provide technical support for the safety of Xiluodu Dam and the reservoir area. The newly established initial underwater landslide-generated surge source model for the mountain reservoir areas may serve as reference for calculation of underwater landslides in other reservoir areas around the world.

Acknowledgments This study was financed by the National Natural Science Foundation of China (ID: 41372321) and the National Key Technology R&D Program (ID: 2012BAK10B01). Additionally, we would like to extend our thanks to friends from Xiluodu Construction Department of the Three Gorges Engineering Construction Corporation, who have brought us to field investigation and provided us with relevant data.

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