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Review

A Review of Research Methods and Evolution Mechanisms of Landslide-Induced Tsunamis

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Abstract: The research on landslide surge has always been a hot issue in the research of engineering geology, geological disasters and hydraulics in both domestic and foreign circumstances. Based on the research status and achievements of landslide surge, this paper mainly reviews the research methods of landslide surge including numerical simulation methods, theoretical analysis methods and physical methods. The first part summarized the examples of geological disaster surge and the classification, characteristics and influencing factors of geological disaster surge. In the second part, the research methods of landslide surge are summarized. Firstly, the theoretical analysis progress of landslide surge in recent years is summarized. Secondly, the present situation of physical model test is summarized from four aspects: model, surge generation, surge propagation and surge run-up. Finally, the numerical simulation methods are summarized from the generation and propagation of surge. The third part discussed the influence factors of landslide surge. In the next part, the difficult problems and research status of landslide surge are evaluated. Finally, the study of landslide surge is prospected from the perspective of various factors of landslide surge.

Keywords: landslide surge; engineering loss example; theoretical analysis; physical model test; numerical simulation

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1. Introduction

The vast territory of China benefits us with abundant material resources. Meanwhile, there are also various geological environments that bring a lot of geological problems. Among them, landslides are one of the common geological problems, which has been studied by domestic and foreign scholars over the years. With a lot of research carried out to deepen the research on landslide-induced issues, attention shifting towards landslide surges has been increased, and it is found that the damage caused by landslide surge is overwhelming [1,2].

The research on surges has always been a hot issue in the field of engineering geology [3,4]. In the beginning, it was associated with earthquake-induced tsunamis. For example, on 28 December 1908 in Messina, Italy, an earthquake with a magnitude of 7.5 triggered a tsunami, resulting in the death of more than 80,000 people. On 11 March 2011, a tsunami, induced by a magnitude 9.0 earthquake that occurred in the eastern sea area of Japan, inflicted huge casualties and economic losses. These cases demonstrate that the occurrence of tsunamis is uncertain and random, which often means devastating disaster.

A landslide surge is the surge developed from the vicinity water resources that are impacted by a landslide or collapse of masses, which threaten the security of buildings and people along its propagation path. Landslide surges mostly occur on the bank slope of a reservoir area. Compared to tsunamis, these landslide-prone areas have more buildings, people and infrastructure. As a result, landslide surges have a greater chance of causing property damage and human casualties. In addition, the development of the economy increased the construction of large reservoirs, especially for the continuous improvement of large water conservancy facilities in recent years, leaving the possibility of landslide surges. Therefore, extensive research has been carried out on the topic of landslide surges. Actually, there are many factors affecting landslide surges [5–11]. It is a complicated geological problem, which is not only influenced by complicated environment and large-scale solid landslide material but also complicated fluid material. To this end, it is challenging to study landslide surges.

The common research methods of landslide surges mainly include theoretical analysis, a physical model test and numerical simulation. Each method has its advantages in different aspects. In terms of theoretical analysis method, it can give an exact solution to a mathematical problem. Meanwhile in the study of the action mode of landslide surge damage, it can be demonstrated more clearly through physical model test. Compared with the model test, the numerical simulation method is low in cost and capable of adapting to the landslide surge damage of complex conditions, which satisfies multi-condition research and repeated simulation. On the basis of consulting a lot of literature, this paper uses real cases of landslide surges to illustrate the destruction of landslide surges; the research methods and progress of slope surge are summarized. Some difficulties and prospects in the study of landslide surge are prospected in the hope of providing some help for the follow-up study of landslide surges.

2. Landslide Surge Cases

The surges have caused awe in humans since ancient times. The records of surges can be sourced from more than a thousand years ago, in which there are many cases of landslide surges recorded hundreds of years ago. With the improvement and development of monitoring systems, more and more landslide surge cases have been recorded. Table 1 lists the major cases of landslide surge worldwide. As can be seen from Table 1, landslide surges are common all over the world. They usually have large landslide volumes and generate surges ranging from tens of meters to hundreds of meters. The landslide surges caused massive casualties.

Table 1. Major cases of landslide surges worldwide.

Number	Time	Location	Landslide Volume (10^4 m^3)	Failure Mode	Number of Deaths
1	1792	Senyun, Japan [12]	535	The formation of 10 m high surge.	15,000
2	1933	Diexi, Minjiang River, China [13]	-	-	8800
3	1956	Lanfjord, Norway [14]	12	The formation of 140 m high surge.	32
4	1958	Lituya landslide in Alaska, USA [15]	30	The formation of 30 m high surge.	2
5	1958	Italy Pontesei arch dam reservoir area [15]	-	A 20 m high surge over the dam.	1
6	1961	Zishui Zhexi Reservoir, Hunan Province, China [16]	1.65	Damage caused by 21 m high surge over dam.	40
7	1963	Italy vajont reservoir [17]	240	A 175 m surge overtop	3000
8	1971	Peru chungar lake shore [15]	0.1	The formation of 30 m high surge.	300–500
9	1980	Mount St. Helens Spirit Lake [18]	2500	The landslide whipped up a more than 200 m high surge	-
10	1982	Jibazi landslide in Yunyang County, Three Gorges Reservoir Area, China [19]	-	The river shoreline advanced inward more than 50 m, the riverbed silt height of 30 m.	-

Table 1. *Cont.*

Number	Time	Location	Landslide Volume (10^4 m^3)	Failure Mode	Number of Deaths
11	1985	Xintan Landslide, Zigui County, Three Gorges Reservoir Area, China [20,21]	30	Initial waves of up to 49 m destroyed nearby ships.	10
12	2002	Stromboli, Italy [15]	-	The formation of 10.9 m high surge.	2
13	2003	Qianjiangping Village in Three Gorges Reservoir Area of China [20]	24	Up to 30 m surges destroyed 120 acres of farmland nearby.	14
14	2007	Shuibuya Dam, China [22]	3	The formation of 50 m high surge.	1
15	2008	GongJiaFang, Wushan, Chongqing, China [23]	0.38	Waves about 15 m high formed on the opposite bank.	-
16	2009	The landslide in Xiaowan	1	The landslide whipped up a 30 m high surge	24
17	2014	Xiaoba landslide in Guizhou province [24]	0.33	The landslide whipped up a 20 m high surge	12
18	2015	Chongqing Wushan Daning River Jiangdong Temple North Shore [25,26]	-	A 6 m high surge toppled nearby boats.	1

2.1. Classification of Landslide Surges

Previous studies have concluded that the important reason for the formation of landslide surge waves can be attributed to the surface gravity wave, which is caused by the external force-induced disequilibrium between the fluid inertia and restoring force. The research about the surface gravity wave can be sourced from two kinds of literature. Herein, the first type of literature, represented by 'Basic wave mechanics: for coastal and ocean engineers' [27], focuses on the further research of water wave dynamics and wave theory, whilst the second kind of literature is represented by 'fluid mechanics' [28]. Fluid mechanics, a branch of mechanics, is the study of the related mechanical behavior of fluids (including gases, liquids and plasmas). Fluid mechanics can be divided into hydrostatics and fluid dynamics according to the motion mode of the object of study. The former studies the fluid at rest, and the latter studies the influence of force on fluid motion. Fluid mechanics according to the scope of application is divided into hydraulics and aerodynamics and so on. Fluid mechanics is a branch of continuum mechanics, which considers the characteristics of a system from a macroscopic perspective rather than a microscopic one [29]. Fluid mechanics mainly use nonlinear theoretical analysis and a modern number sequence method to describe the characteristics of water flow. The theory of water wave dynamics holds that the wave of landslide surges belongs to the category of gravity waves, which satisfies or roughly satisfies the constraint of wave theory formula. However, the wave property of landslide surges is ignored in fluid mechanics, which directly calculates the water particles.

According to the relative position of the landslide and water surface, the landslide surge waves can be classified into three types [30]: (1) landslide surges induced by the collapse masses above water surface, which involves the movement of solid, water and air, (2) landslide surges induced by collapse masses that are partially under water surface and (3) landslide surges induced by underwater collapse masses. Three positional relationships are shown in Figure 1.

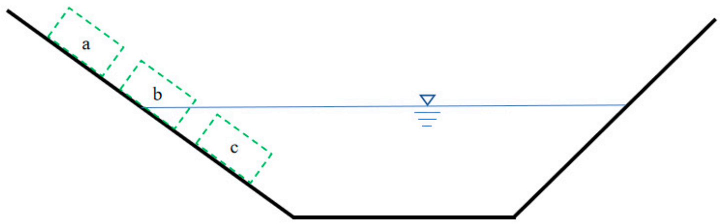

Figure 1. Relative position of landslide and water (**a**) landslide surges induced by the collapse masses above water surface, which involves the movement of solid, water and air. (**b**) landslide surges induced by collapse masses that are partially under water surface. (**c**) landslide surges induced by underwater collapse masses.

2.2. Study on the Mechanism of Landslide Surge

According to the classification of the description parameter of wave theory, the characteristics of landslide surges are more complex. Most landslide surge waves are non-periodic waves and have strong nonlinearity, which are between moderate water waves and shallow water waves [31,32].

Through 211 groups of physical similarity tests, Valentin Heller [33] found that the height of surge wave is generally 5/4 times of the wave amplitude, and the wave velocity is generally close to the theoretical velocity of solitary waves.

Along the same line, Noda, Huber, Panizzo, Zweife et al. [34,35] found that different forms of surge waves are formed when the Froude coefficient (F), the relative thickness of the block (S), the relative mass (M) and the effective impact angle of the landslide (β) are different.

Panizzo, Zweifel, Yin et al. [36] carried out a large number of similarity tests of the landslide surge and found that the maximum height of surge is controlled by seven factors, including the water-entry velocity of the collapse masses of landslide, the thickness and width of the collapse masses, the volume and density of the collapse masses, the impact angle and the water depth. The test results also demonstrate that the wave height approximately satisfies a specific empirical formula. Besides, the wave height of the propagation wave is a more complicated problem. It is influenced by more factors, which are not only affected by the maximum height of surge but also the river surface and landform along the propagation path.

While Kamphuis et al. [9] deemed that the effect of sliding impact angles is negligible, Heller et al. [28] believed that wave height is related to $\cos(6/7\alpha)$ and negatively correlated with α. These research results show that the influence multiple of different impact angles is varied between 0.5 and 1.95. However, in many physical similarity tests, velocity and sliding impact angle are interrelated, which leads to the difference of the above research conclusions. In addition, even different shapes of masses entering the water will induce different surges.

The study of Xu [37] used the coupled Eulerian–Lagrangian (CEL) algorithm and a variety of orthogonal numerical experiments and found that the influence of landslide shape on landslide surge, which is more significant within the near field. Besides, the volume of the landslide has a great influence on the height of the surge, and the influence decreases with the increase of the propagation distance.

Watts [38] pointed out that the deformation of the moving deformable masses is controlled by the motion of its centroid, and the difference between the surge generated by the deformable masses and the rigid body (with the same initial shape as the deformable masses) is inconspicuous.

The above research and investigation indicate that the occurrence of landslide surge is caused by the interaction of many factors. Due to the frequent occurrence of landslide surge in recent years and the complexity and diversified characteristics of landslide surge, many scholars have used a variety of research methods to study landslide surge from multiple angles, and the research on landslide surge has gradually become mature and perfect. The following is a summary of current landslide surge research methods from the perspective of different research methods.

3. Landslide Surge Research Methods

3.1. Theoretical Analysis of Landslide Surge

3.1.1. Surge Generation Stage

Compared with numerical simulation and physical model experiments, theoretical analysis can attain an exact solution of a closed idealized mathematical problem. Based on the energy conservation law, Noda [35] assumed that the reservoir area is a semi-infinite water body and the landslide body is a rigid body. In this case, the landslide body movement can be regarded as the motion of its centroid. Figure 2 is a schematic diagram of the landslide

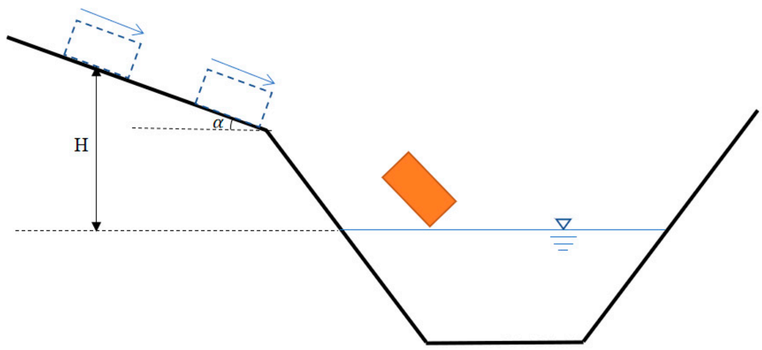

Figure 2. Schematic diagram of landslide.

Therefore, the water-entry velocity of landslide body can be expressed by Equation (1):

$$v = \sqrt{1 - \cot\alpha \tan\varphi - \frac{cl}{mg\sin\alpha}}\sqrt{2gH} \tag{1}$$

where v is the water-entry velocity of landslide body; α is the sliding angle; φ, c is the shear strength parameter of sliding surface; m is the weight of the landslide body; H is the distance from the centroid of landslide body to the water surface; l is the length of the contact surface between the landslide body and sliding surface; g is the local gravity.

The study of Noda [35] simplified the landslide body into a rectangular rigid box, and the height H was set to be greater than the depth of dead water. This is to eliminate the impact of the height of landslide body on surge. The process of surge caused by the impact of rigid box is expressed as:

$$\frac{\eta(x,t)}{\lambda} = \frac{2}{\pi} \times \int_0^\infty \frac{du}{u} \int_0^T \frac{\sin\{hu[1-s(\tau)]\}\cos(ux)V(\tau)d\tau}{[1-s(\tau)]\cos(hu)} \tag{2}$$

where $\eta(x,t)$ denotes the elevation of the wavefront at the coordinate x and time t, λ is the width of the rigid box, T is the time duration for velocity to decrease from the water-entry velocity to 0, V is the velocity of the rigid box in water, s is the moving distance of the rigid box in water, $\sigma = \sqrt{\frac{\tan(hu)}{u}}$, $u = kh$, k is the wave number, h is the depth of dead water and τ denotes an extremely short time interval. The limitation of this analytical solution is that the effects during the box impacting the free surface of water and the stage of underwater motion on the surge are not considered.

Based on Noda's research, Di et al. [39] proposed a new analytical solution of initial surge under the framework of linear theory, which considered the limitation of Noda's method.

By using the one-dimensional linear shallow water equation, Liu et al. [40] derived the analytical solution of the surge generated by landslide in two-dimensional model. The expression of wavefront elevation generated under the uniform sliding velocity of landslide body is:

$$\eta(\xi,t) = \frac{1}{3}\left(h_0 - \xi\frac{\partial h_0}{\partial \xi}\right) + \int_0^\infty \omega a(\omega) J_0(\omega\xi)\cos(\omega t)d\omega + \int_0^\infty \omega b(\omega) J_0(\omega\xi)\sin(\omega t)d\omega \tag{3}$$

where J_0 is the zero-order Bessel function of the first kind; $a(\omega)$ and $b(\omega)$ are spectral functions determined by initial conditions; ω is wave frequency; ξ is a wavefront function.

Pan [35] combined the study of Noda [35] with the linear wave theory. This study divided the landslide into several blocks, and the interaction force between the blocks is assumed to be ignored; then, the landslide velocity of the first block is expressed as:

$$V_{xi} = \sqrt{2a_{x(i-1)}\Delta L + V_{x(i-1)}^2} \tag{4}$$

where V_{xi} is the landslide velocity of the ith block; $a_{x(i-1)}$ is the landslide velocity of i blocks; ΔL is the width of the ith block.

Based on the momentum theorem, Wang et al. [30] analyzed the landslide surge by the slice method and obtained the calculated height of the initial surge by the momentum theorem:

$$\eta = \eta_i + \frac{H_i}{2} - h_0 \tag{5}$$

$$\eta = \frac{m_i v_i}{H_i B_i t_i \rho g} \tag{6}$$

where η is the calculated height of the initial surge, m_i is the weight of the landslide body, v_i is the velocity of the landslide body, t_i is the time duration of the landslide body moving underwater, H_i is the height of the landslide body, B_i is the width of the landslide and η_i is the distance from the centroid of the landslide body to the highest point of the surge.

Based on the Noda method, Wang et al. [36] believed that the underwater movement of the landslide body has no impact on the water surface and would not cause a surge. Therefore, the H in the expression for calculating the water-entry velocity of the landslide body should be modified as H', which should be the distance between the centroid of the underwater part of the landslide body and the water surface. The expression is modified as:

$$v = \sqrt{1 - \cot\alpha\tan\varphi - \frac{cl}{mg\sin\alpha}}\sqrt{2gH'} \tag{7}$$

Dai et al. [19] deemed that the Noda method does not consider the resistance of water on the landslide body after entering the water. They consider the water resistance is $R = \frac{1}{2}c_w\rho_f v^2 S$, and the calculation expression of the initial sliding velocity after considering the water resistance is derived:

$$v = \sqrt{\frac{2H(mg\sin\alpha - mg\cos\alpha\tan\varphi - cL)}{(m\sin\alpha + Hc_W\rho_f S)}} \tag{8}$$

Additionally, Dai et al. [19] also believed that the slice method proposed by Pan could not accurately describe the shape of the landslide surface, so they proposed using the motion equation method to calculate the initial sliding velocity of the landslide, and the acceleration calculation is improved by the motion equation method:

$$a_i = \{\sum_i^k (W_i\sin\theta_i - \mu_i\cos\theta_i) + \sum_i^k P_{w_i}[\cos(\alpha_i - \theta_i) - \mu_i\sin(\alpha_i - \theta_i)] - \sum_i^n c_i L_i\}/\sum_{i=1}^n M_i \tag{9}$$

where W_i is the weight of the ith block; c_i is the cohesive force of the slip band of the ith block; L_i is the ground length of the ith block; θ_i is the inclination angle of the ith block; μ_i is the dynamic friction coefficient of the ith block; k is the number of blocks.

Some scholars have explored the generation mechanism of other waves except landslide surge wave through theoretical analysis [41,42]. Haugen et al. [43] studied the basic mechanism of tsunami generated by underwater mass flow under ideal geometric conditions through a two-dimensional linear analysis model. Ursell et al. [44] proposed the classical small amplitude wave theory of the piston generates wave, but this theory is only applicable to the small amplitude motion of plate. Kennard [45] developed a linear theory of waves, and Das et al. [46] determined that the linear theory proposed by Kennard has to satisfy the following three conditions: (1) the displacement of the vertical wall must be smaller than the dead water depth; (2) the acceleration of the wall must be less than the gravity; (3) the sliding constant must be less than unit 1.

3.1.2. Propagation Stage

By assuming that the coastline is a parallel steep face, Pan [47] ignored the energy attenuation in the process of surge propagation and the nonlinear influence of boundary conditions. The surge propagation processes are regarded as the linear superposition of a series of wavelets generated from the source point, where each wavelet is a solitary wave and has a total reflection on the opposite bank of the reservoir. Assuming that the reflection coefficient is known, the calculation expression of landslide surge height is obtained:

$$\zeta = \frac{2\zeta_0}{\pi}(1+k) \times \sum_{n=1,3,5\cdots}^{n} \left\{ k^{2(n-1)} \times \ln\left[\frac{l}{(2n-1)B} + \sqrt{1+\frac{l^2}{(2n-1)^2 B^2}} \right] \right\} \tag{10}$$

where ζ is the surge height on the opposite bank of landslide; ζ_0 is the initial surge height on the opposite bank of the landslide; k is the reflection coefficient of surge; B is the width of the river; n are the times of reflections. The calculation expression of landslide surge height at downstream dam site is expressed as:

$$\xi = \frac{\xi_0}{\pi} \times \sum_{n=1,3,5}^{n} (1 + k\cos\theta_n) k^{n-1} \times \ln\left\{ \frac{\sqrt{1+\left(\frac{nB}{x_0-L}\right)^2} - 1}{\frac{x_0}{x_0-L}\sqrt{1+\left(\frac{nB}{x_0}\right)^2} - 1} \right\} \tag{11}$$

where ξ is the surge height on the opposite bank of landslide; ξ_0 is the initial surge height at the downstream dam site; x_0 is the distance from the centroid of the landslide to the downstream dam site; θ_n is the intersection angle between the nth incident line and normal line of bank slope.

Wang et al. [30] studied the attenuation of surge in the propagation process and deemed that the propagation stage of surge in the river is divided into a sharp attenuation stage and a slow attenuation stage. Based on the continuity equation and motion equation of unsteady flow of open channel, the calculation expression of landslide surge in the sharp attenuation stage is obtained:

$$h_s(x,t) = h_1 e^{-\sqrt{k_1}x - \sqrt{\frac{g}{h_j}}t} \tag{12}$$

where h_s is the height of surge with a distance of x from the landslide occurrence point, h_1 is the wave height and h_j is the initial surge height; $k_1 = \frac{T_0 a^2 - gkT_0 a}{A_0 g}$, T_0 is the initial width of the water surface; x is the ratio of actual propagation distance to water depth; t is propagation time in sharp attenuation stage.

The calculation expression of landslide surge in slow attenuation stage is:

$$h_s(x) = h_1' - \frac{2g(h_0 + h_1')^2 n^2}{(2h_0 + h_1')R^{\frac{4}{3}}} x' \tag{13}$$

where h_1' is the height of surge with a distance of x from the landslide occurrence point; h_0 is water depth; n is the roughness coefficient; x' is the propagation distance in the slow attenuation stage; R is the hydraulic radius.

Li et al. [48] regarded the propagation process of landslide surge as a process of the interaction between a shock wave and a rarefaction wave. The interaction between the shock wave and rarefaction wave is qualitatively obtained by adopting the shallow water wave equation, mass coordinate and velocity wave height curve method:

When

$$u_r < u_l - \sqrt{\frac{g(h_r + h_l)(h_r - h_l)^2}{2h_r h_l}} \tag{14}$$

an incident shock wave will be generated.

When

$$u_r > u_l - \sqrt{\frac{g(h_r + h_l)(h_r - h_l)^2}{2h_r h_l}} \tag{15}$$

an incident sparse wave is generated.

u_r and h_r are, respectively, the right side flow velocity and water depth before the interaction between rarefaction wave and shock wave, while u_l and h_l denote the flow velocity and water depth on the left side before the interaction. According to the mass conservation equation, Li calculated the wave velocity of the shock wave produced by the interaction between the rarefaction wave and the shock wave:

$$D = u_0 + \sqrt{gh_0}\sqrt{\frac{1 + h_1/h_0}{2}} \tag{16}$$

where D is the velocity of shock wave; h_0 is the water depth of shock wave front; u_0 is the flow velocity of the wave front of shock wave; h_1 is the water depth of the wave back of shock wave; u_1 is the flow velocity of the wave back of shock wave.

Based on the study of Pan, Ha et al. [49] considered the phase difference of wave superposition during propagation, and the calculation expression of surge height at the opposite bank and dam site of landslide reservoir area was modified:

$$\begin{aligned} \zeta' &= (1 + K)\zeta \\ \zeta'' &= (1 + K\cos\theta)\zeta \end{aligned} \tag{17}$$

where ζ is the wave height before reflection, 2 is the reflection wave height, 3 is the secondary reflection wave height, K is the reflection coefficient, and θ is the incident angle.

From the perspective of energy, Law [50] made a qualitative study on the propagation process of the landslide surge. The study found that the energy of the initial wave accounts for 98% of the total energy of the landslide surge, and the attenuation of the initial wave is inversely proportional to the square of the propagation distance along the propagation path.

Meanwhile, Hunt [51] made a judgment on the selection of the calculation theory of landslide surge: when the landslide occurs rapidly and the transverse size of the underwater part of the landslide body does not exceed twice of the water depth, the generated surge is short-wave. If the transverse size of the landslide body exceeds 10 times of the water depth, the generated surge wave is long-wave.

3.2. Physical Model Test Method

According to the development of the landslide surge, the evolution process can be divided into three stages, namely, the generation stage, the propagation and attenuation stage and the climbing stage. Figure 3 shows the stages of landslide surge.

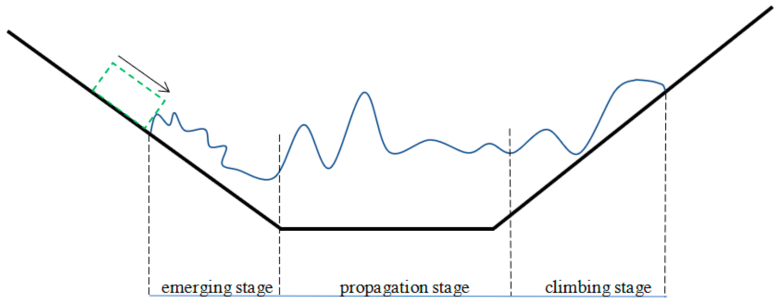

Figure 3. Schematic diagram for three stages of landslide-generated impulse waves.

3.2.1. Physical Model

Landslide surge is affected by many factors such as landslide body, water body and terrain. Therefore, there are certain advantages to generalizing the landslide body and water body into a simple physical model. However, this may impact the reliability of test results. Domestic and foreign scholars have optimized the physical model method constantly to attain the robust reflection of the real damage.

In 1955, Wiegel [52] carried out physical model tests by adopting steel plates to simulate landslide blocks.

Noda [35] and Pan [47] focused on the surge induced by horizontal and vertical landslides. The model was generalized into a cuboid thereby ignoring the influence of the shape of the landslide.

Ashtiani [53] considered the influence of landslide shape by using sand-gravel particle material to make granular model.

Considering that the particle model can only simulate the loose particle landslide, Yin et al. [5] applied the river physical model to simulate the water surface, while the granular materials and cement were adopted to fabricate different sizes of landslide body. Meanwhile, in order to reconstruct the real process of landslide surge and fully consider the complexity of landslide surge, the landslide inclination and water-entry speed were controlled by means of the test control system, which significantly improved the flexibility of the test.

Other scholars have used different materials to simulate slides. For example, Han et al. [6] used multiple rigid blocks with sizes controlled by structural planes in the three directions (length, width and thickness) to simulate the landslide body. Viroulet et al. [2] used glass beads of different sizes and shapes to simulate the landslide body.

With the deepening of the research on the simulation of physical model test slope, some scholars consider the similarity between the test model and the prototype. Huang et al. [8] investigated the Gongjiafang landslide. The marble rock which is high in similarity in terms of density with the main compositions of the prototype landslide was adopted to simulate the landslide body, in order to ensure the similarity principle. Wang et al. [11] simulated the water body by using the river generalized model and used concrete, steel bars, plastic plates, plastic pipes and other materials to simulate the wharf in Wanzhou Port. The parameters including the hull shape, full load displacement and draft depth were designed to meet the similarity relationship.

Some scholars not only simulated the disaster factors but also restored the disaster process of the carrier when landslide surge occurred. Chen et al. [18] studied the safety of mooring ships under landslide surge by replicating the river section of Tuokou wharf in Jiangnan, Wanzhou, and a deck barge of 3000 t was selected as a test ship. In addition, some scholars designed a pneumatic landslide-generating device to simulate landslide surge, which can greatly improve the test repeatability and accurately, and all the important parameters of surge can be controlled.

3.2.2. Surge Generation Stage

As an important part of the landslide surge disaster, the generation stage of surge has been studied by many scholars through physical model tests.

Noda [35] carried out theoretical derivation through physical model test and first proposed the initial wave equation under the impact of horizontal landslide:

$$\frac{H_{\max}}{\mathrm{h}} = 1.17\frac{v}{\sqrt{gh}} \tag{18}$$

Based on Noda's research, Pan [42] continued to carry out physical model tests and proposed the initial wave calculation equation of vertical landslide surge.

$$H_{\max} = \begin{cases} \frac{v}{\sqrt{gh}}, (0 < \frac{v}{\sqrt{gh}} < 0.5) \\ f\left(\frac{v}{\sqrt{gh}}\right), (0 < \frac{v}{\sqrt{gh}} < 2) \\ 1, (\frac{v}{\sqrt{gh}} > 2) \end{cases} \tag{19}$$

Wang et al. [11] studied the landslide surge of mountain channel reservoir by a 1:70 scale model test and proposed the equation of total wave energy of initial wave:

$$E_w = PTS = \frac{1}{8}\rho g H^2 LSn \tag{20}$$

where

$$n = \frac{1}{2}\left[1 + \frac{2kh}{\sin(2kh)}\right] \tag{21}$$

H is the initial wave height, S is the length of the peak line of the initial wave, c is the wave velocity, and L is the wavelength. When the water level is high, $n = 1/2$; when the water level is low, $n \approx 1$.

Ke et al. [54] carried out physical model tests based on a river of Wushan County and Fengjie County. The correction coefficient K shown in Equation (22) was proposed. Then, the correction coefficient was validated by taking the Gongjiafang landslide as an example.

$$K = 2.30\left(\frac{v_s}{\sqrt{gh}}\right)^{-0.93}\left(\frac{sb}{h^2}\right)^{0.43} \tag{22}$$

Through the physical model test, Peng et al. [50] designed an orthogonal test scheme comprised of six factors which affect the landslide surge. The results demonstrated that the water level of the landslide body entering the water and the thickness of the landslide body are important factors to control the initial wave height of the landslide surge. The accordingly fitting empirical equation of the initial wave is obtained:

$$\left(\frac{s}{h}\right)^{0.462} \times (\tan\alpha)^{-0.379} \tag{23}$$

Yin et al. [5] transformed the experimental data into dimensionless form and optimized the maximum initial wave equation of landslide obtained by a previous study which is expressed as Equation (24):

$$\frac{H_{\max}}{h} = 1.17\frac{v}{\sqrt{gh}}(\sin^2\alpha + m\cos^2\alpha)g_1\left(\frac{lt}{bh}\right)g_2\left(\frac{w}{b}\right) \tag{24}$$

The equation for calculating wave propagation was obtained by the multivariate nonlinear regression method:

$$\frac{H_p}{h} = 1.47\frac{H_{\max}}{h}\left(\frac{x}{h}\right)^{-0.5}, \left(\frac{x}{h} > 2.13\right) \tag{25}$$

While the equation for calculating wave at climbing stage is

$$\frac{R}{h} = 2.3\frac{H_c}{h}(\frac{90}{\beta})^{0.2} \tag{26}$$

Kamphuis et al. [7] conducted a landslide surge test in a two-dimensional flume, in which the angle of the landslide was controlled between 20° and 90°. Besides, the dimensionless relation of initial wave height is determined by dimensional analysis:

$$\frac{H}{h} = f(Fr, L, S, \alpha, \varphi, n, D, X, T) \tag{27}$$

where Fr is the sliding Froude number; L is the relative landslide length; S is the relative landslide thickness; α is the sliding dip angle; φ is the angle of the front of landslide; n is the porosity of landslide; D is relative landslide density; x is relative propagation distance; T is relative time. Herein, the influence of Fr, L and S is the most conspicuous.

Walder et al. [55] studied the near-field surge generation area through a two-dimensional flume model, in which the motion characteristics of the landslide model were recorded, and the dimensionless expression of the maximum amplitude of the near-field surge was accordingly derived:

$$\frac{a_m}{h} = 1.32(\frac{T_s}{V})^{-0.68} \tag{28}$$

where T_s is the time duration of the relative underwater motion of the landslide; V is the relative landslide volume, and a_m is the maximum amplitude.

Based on the momentum balance theory, Han et al. [6] derived the theoretical expression of the maximum near-field amplitude of surge under hydrostatic and fluctuating conditions:

$$a_{m1} = \sqrt{h^2 + \frac{2\rho_s sbv_s^2 \cos\alpha L}{\rho g K}} - h \tag{29}$$

$$a_{m2} = \frac{2\rho_s sbv_s^2 \cos\alpha}{\rho g h T(s + b/2)} \tag{30}$$

where a_{m1} and a_{m2} are the maximum amplitude under hydrostatic conditions and fluctuating conditions, respectively; b and s are the width and thickness of the landslide; v_s is the velocity of the landslide along the slope direction; h is the dead water depth; α is the angle of landslide body; ρ_s is the density of the landslide body; ρ is the density of the water body, and T is elliptic coefficient.

Huang et al. [56] established a 1:150 experimental model based on the Lechangxia reservoir. The characteristic of landslide surge with respect to different water-entry velocities and water level conditions was investigated, and the test results were compared with the theoretical results of Pan Jiazheng method, the method recommended by the American Civil Engineering Society and the empirical equation method of the Academy of Water Sciences. The results demonstrated that the Pan Jiazheng method is more accurate in the case of applying the empirical equation method to predict the surge.

Huang et al. studied the influence of water entry velocity and water level conditions on the generation of surge wave but ignored the influence of landslide volume on the generation of surge wave. Therefore, some scholars have explored the influence of landslide thickness and width on the generation and propagation of surge waves. Yuan et al. [3] studied the generation and propagation law of surges subjected to landslides with different widths and thicknesses within the curved channel. The results illustrated that the surge height is proportional to the width and thickness of landslide.

In order to explore the influence of more factors on landslide surge wave, the landslide surge wave height formula was obtained. Based on the channel model of a hydropower station on the Lancang River, Ding et al. [57] used the orthogonal test method to carry out the landslide surge test. The effects of influencing factors such as landslide size, water-entry velocity, water depth and river width on the maximum initial wave height, as well as the regularity of wave propagation, were studied. The equation for calculating the maximum initial wave and the propagating wave were fitted by the method of multiple regression. In addition, Li et al. [58] took the reservoir area near the dam as the research object to analyze the variation law of surge height under different landslide factors such as shape, water depth, volume and falling height in the narrow channel. He concluded that the height of the surge is proportional to the sliding height and the volume of the initial drainage and inversely proportional to the water depth. Xiao et al. [59] established a 1:200 river channel model to study the influence of different factors on the characteristics of the water tongue and the height of the initial wave in the near-field region. The empirical equation for calculating the height of the water tongue and the length of the water tongue were, respectively, obtained by the fitting variance method and the regression method. The reliability of the equations was verified by the cases of the Dayantang landslide and the Qianjiangping landslide.

In order to explore the damage pattern of surge in different scenes and bank slope shapes, McFall [60] studied the characteristics of surge in more scenarios based on model experiments, including open seas, narrow fiords, curved straits and conical islands. The results show that the initial wave crest amplitude generated by the landslide along the plane is greater than that along the conical island slope. However, the amplitude of the initial wave trough and the second wave crest is smaller than that of the conical island. In addition, the energy conversion rate of the landslide kinetic energy was within the range of 1% and 24%, and the energy conversion rate of pebble landslide was 43% larger than that of gravel landslide on average.

In addition, some scholars have adopted some special methods to make the physical model test of landslide surge wave better reflect the real damage situation. Mohammed et al. [61] conducted a series of granular landslide surge experiments in a three-dimensional wave basin. The model landslide body adopted natural circular river gravel with a particle size of 12.7–19 mm. The landslide movement was controlled by a new pneumatic landslide surge generator fixed on a slope. Based on the experimental results, the empirical equation of near-field wave was obtained by using multivariate regression analysis method, which is mainly related to sliding Froude number, relative landslide thickness, relative landslide width and relative landslide length.

Some scholars design experiments based on some field investigation data to propose risk analysis methods. Liu et al. [62] established a 1:200 physical model based on the Baishui River landslide channel, and the geological data of more than 100 potential landslides in the Three Gorges Reservoir area were statistically analyzed. Generally, the three-dimensional physical model test was performed within the scheme of the orthogonal test. The velocity calculation model of wading landslide after instability was accordingly proposed, which was fed as the calculation model for the landslide surge in the Three Gorges Reservoir area after the sensitivity analysis method. Heller et al. [31] discussed the scale effect in the landslide surge model experiment and deemed that when the water depth of the model is less than 0.2 m, the scale effect caused by fluid viscosity and surface tension cannot be ignored. Besides, the landslide surge tests with respect to four different granular materials were conducted by using the Fritz experimental device. In the experiment, the deformation of the granular landslide and the velocity of its centroid before entering water was captured by the two laser distance sensors arranged above the slide. By analyzing the maximum surge in the near field, it was found that the surge wave height is about 5/4 times of the wave crest amplitude, indicating that the nonlinearity of the near field surge is conspicuous, and the wave velocity can be approximately described by the solitary wave velocity. Moreover, the test also demonstrated that the empirical equation of surge characteristic parameters caused by granular landslide is related to a dimensionless parameter P, which is called surge generation parameter.

$$P = FrS^{1/2}M^{1/4}(\cos\beta)^{1/2} \tag{31}$$

In this formula, Fr is the sliding Froude number; S is the relative landslide thickness; M is the relative landslide mass, $\beta = (6/7)\alpha$; α is the angle of landslide.

3.2.3. Propagation Process Stage

After the landslide body enters the water for a period of time, due to the propagation of surge energy in space, frequency diffusion and nonlinear effects, the surge wave height will gradually decrease as the propagation distance increases [63]. The purpose of studying the propagation stage of landslide surge wave by physical model test is to analyze the attenuation rule and put forward the empirical equation through the experimental data. Li et al. [64] established a flume experiment model based on the Three Gorges Reservoir, and the variation law of initial surge height subjected to different angles of landslide slope, solid-fluid effective contact surfaces and water depths was investigated. The regression analysis was applied to analyze the link between the wave height and the three factors. The empirical equation of relative initial surge height and wave height of different landslide water-entry points was, respectively, fitted, and the data error verification analysis was accordingly carried out. Finally, two empirical equations for calculating surge height along the propagation path were proposed, which provides a basis for calculating surge height at different positions. Yang et al. [65] studied the attenuation law of the initial surge height along the river channel by taking the steep rock landslide in the Three Gorges Reservoir area as the research object through model test and summarized the wave height attenuation relationship. The wave height attenuation coefficient was divided into two stages by the propagation distance of 3 m. The empirical equations for calculating the wave height attenuation coefficient at different stages were proposed. Finally, the applicability of the empirical equations was verified by the experimental results.

3.2.4. Surge Climbing Stage

The study of surge climbing process through physical model test is mainly aimed at the factors which affecting the climbing process, such as bank slope angle, bank slope permeability and so on. In response to these factors, scholars have adopted many different wave-making methods to generate surge waves.

Hall and Watts [66] simulated the generation of solitary waves through a piston wavemaker at the Waterway Experiment Station (WES) of the U.S. Army Corps of Engineers and studied the climbing process of solitary waves on impervious bank slopes. Through experiments, it was found that when $\beta < 12°$ (β is the bank slope angle) the maximum wave height is mainly affected by friction, while when $\beta < 12°$, the maximum wave height is mainly affected by gravity and inertial force. The empirical formula of the maximum solitary wave height was obtained by fitting the experimental data:

$$\begin{cases} \frac{r}{h} = 11\beta^{0.67}\left(\frac{H}{h}\right)^{1.9\beta^{0.35}} (5° \leq \beta < 12°) \\ \frac{r}{h} = 3.05\beta^{-0.13}\left(\frac{H}{h}\right)^{1.15\beta^{0.02}} (12° \leq \beta \leq 45°) \end{cases} \tag{32}$$

Synolakis [67] proposed an approximate theory of unbroken solitary wave propagation under the condition of constant water depth. The model test was carried out at a slope of 1:19.85, and the theoretical derivation results were compared with the experimental data. It was found that the theoretical derivation results were basically consistent with the experimental data when the solitary wave was not broken. The unbroken solitary wave climbing equation is called the "climbing law".

$$\frac{r}{h} = 2.831(\cot\beta)^{1/2}\left(\frac{H}{h}\right)^{5/4} \tag{33}$$

Müller [68] used Russell's wave-making method to generate surges through falling heavy objects. The process of surge climbing and dam overflow with respect to slopes of 18.4°, 45° and 90° was, respectively, investigated. The prediction equation of surge climbing is expressed as:

$$\frac{r}{h} = 1.25\left(\frac{90^\circ}{\beta}\right)^{0.2}\left(\frac{H}{h}\right)^{1.25}\left(\frac{H}{L}\right)^{-0.15} \quad (34)$$

3.3. Numerical Method

3.3.1. Surge Generation Stage

The study of surge generation involves the interaction between landslides, reservoir water and air. Therefore, it is an important problem to simulate shock generation in numerical simulation of landslide surge [69,70].

The tracking of free surface is an important research topic in the simulation of surge generation. Accurately capturing the free surface of the fluid can truly simulate the generation process of surge. At present, the VOF method, SPH method, MAC method and LEVEL SET method have been applied to the study of this problem and have achieved good results. The LEVELSET method is more convenient to solve and easier to deal with complex interfaces and dramatic changes in free surfaces. Some scholars use this method to study the influence of surge and verify the applicability of CEL method in the study of landslide surge by comparing with the experimental results. However, the research is mainly aimed at a single block landslide and does not consider the granular landslide. The smooth particle hydrodynamics method (SPH) was originally applied to the calculation of irregular motion in three-dimensional space. Compared with the finite difference analysis method, SPH uses particle to represent the medium fluid to estimate the partial differential equation based on multiple variables [71].

$$< f(x) >= \int_E f(x')W(x-x',h)dx' \quad (35)$$

In the formula, $< f(x) >$ denotes the kernel estimate at coordinates; $f(x')$ is the field value; $W(x,y)$ is the kernel function. In recent years, more and more scholars have applied the SPH method to the field of fluid mechanics, which is suitable for simulating large surges caused by high-speed landslides.

The VOF method has strong advantages in dealing with free boundary problems and has good adaptability to large deformation. At the same time, it requires a small amount of storage, which is widely used in research.

Li et al. [72] used the finite volume method to establish the calculation model and discussed the mechanism of surge generation. The fluid calculation software FLUENT combined with dynamic mesh technology and VOF method was adopted to compare and analyze the surge height and pressure field generated by different landslide models.

Based on the Navier–Stokes equations, Song et al. [73] used the VOF method to simulate the generation process of surges. The simulation results were in good agreement with the experimental results and the observation results. Yuk et al. [74] used the VOF method to simulate the process of landslide surge generation, and the free surface was effectively tracked. Abadie et al. [75] described the air, water and landslide with Newtonian fluid and Navier–Stokes equation and simulated the surge by combining them with the VOF method. This research pointed out that the air also had a significant influence on the motion of landslides, but the research works of Abadie et al. were limited to rigid landslides.

Liu et al. [76] used the VOF method and LES model to study the phenomenon of water climbing and falling caused by the sliding of three-dimensional regular blocks. Based on the shallow water wave equation, the generation and propagation of landslide surges under a variable grid were simulated by using dynamic grid technology under the premise of known landslide movement. The results were compared with the experimental data, which showed that the dynamic grid technology can simulate the surge accurately.

3.3.2. Propagation Process Stage

There have been a lot of research results on surge propagation simulation, and most of these numerical models can directly be applied in research. In terms of the research method, the empirical equations have a certain impact on the accuracy of the calculation results since they are obtained based on idealized assumptions. Therefore, the numerical calculation can simulate the surge propagation more accurately than the empirical equations.

The numerical models of surge propagation mainly include the Navier–Stokes equation model, Boussinesq equation model, the model based on shallow water wave equation, etc.

Some scholars applied the N-S equation of fluid mechanics and established finite element and finite difference methods to analyze specific landslides; the height of the surge was obtained, and the law of energy exchange between landslides and water bodies was studied [77]. Ren et al. [78] derived the DIF equation for simulating landslide surge and used the irregular grid finite product method and the explicit MacCormack prediction-correction numerical method to solve the equation. The numerical model of landslide surge was established and verified by the relevant data of Xintan landslide. Xu et al. [79] adopted the Navier–Stokes equation model in the FLOW3D software and the VOF method to simulate the generation and propagation of surges in three-dimensional wide waters. Compared with the experimental results, it is indicated that the numerical model can well simulate the generation and propagation of surges, but it ignored the influence of slider form on surges, and the simulation accuracy needs to be improved.

By adopting the shallow water equation, Bosa et al. [80] established a 2DH numerical model to simulate the surge caused by the Vajont reservoir landslide. The results show that the shock wave caused by the large landslide can be simulated by the two-dimensional model.

Based on the two-dimensional fourth-order Boussinesq equation model, Ashtiani et al. [81] simulated the surge height, wave climbing and maximum wave height of Maku and Shafa-Roud reservoir areas, which provided a reference for further evaluating the surge disaster caused by potential landslides in the reservoir area.

In addition, through the secondary development of GEO-WAVE software, Wang et al. [82] established FAST system to study the propagation and attenuation law of surge and established a surge warning system, which has a good application prospect. Huang et al. [15] used GEOFLOW to simulate the propagation process of surges and discussed the propagation law of surges. Heidarzadeh et al. [83] used the TUNAMI-N2 numerical model to simulate the propagation of tsunami caused by submarine landslides.

In order to verify the accuracy of the numerical model, some scholars use the landslide prototype to verify. Jiang et al. [84] established a numerical model of landslide surge by solving the DIF equation and verified it by the Xintan landslide. However, it assumed that the landslide was a single block with a fixed shape, which ignored the impact of the shape of rock landslide on the surge. Shen et al. [85] simulated the propagation process of elliptic cosine waves, in which the VOF method was used to deal with the problem of wave free surface, and the simulation results were consistent with the experimental results.

4. Study on Influence Factors and Mechanism of Landslide Surge

The formation of landslide surge is a multidisciplinary problem involving landslide dynamics, rock and soil mechanics and fluid mechanics. Many scholars use numerical simulation, a physical model test and other methods to study the factors affecting landslide surge [86], and some patterns were found, including the following research results.

4.1. Sliding Body Factor

The study of sliding body factors mainly involves the landslide shape, volume of the sliding body and friction angle of the sliding surface. Through the study of the relationship between landslide shape and surge, it is found that the surge formed by wedge-shaped sliding mass is the largest, subsequently the rectangle, while the surge provoked by the oval block is the smallest. The surges induced by the rectangular and wedge-shaped sliding masses are generally the same when the water-entry point is far, but they are larger than those induced by elliptical blocks. Additionally, through the study of the relationship between the volume of the sliding mass and the surge, it is found that the volume of the sliding mass has a great influence on the surge height, especially in the near field condition. Scholars believe that the volume of the landslide is the most important factor controlling surge size. Through the study of the relationship between the friction angle of the sliding surface and the surge, it is found that the internal friction angle of the sliding surface has a great influence on the surge height under the same height. The friction angle of sliding surface affects the surge size by changing the velocity of sliding body entering water [38].

4.2. Water Body Factor

Among the water factors, the main factors that have a great influence are the width of the water surface and the distance between the sliding body and the water. Through the study of the relationship between water surface width and surge, it is found that when the surge reaches the opposite bank, the effect of the opposite bank on the surge gradually increases due to the blocking effect. With the decrease of water surface width, the surge height shows a slight increase trend, especially the climbing height. While studying the height of a landslide in water, it was found that with the increase of the distance from the water-entry point, the influence of the front edge shape and the volume of the sliding on the landslide surge gradually decreases [47].

5. Difficulties and Problems of Landslide Surge Research

Although there are many research methods on landslide surge, there are still many problems and difficulties. This section summarizes the difficulties in the current research on landslide surge from three perspectives: theoretical analysis, a physical model test and numerical simulation.

5.1. Theoretical Analysis Method

The theoretical analysis method is a simple and fast surge estimation method based on mathematics and mechanics. The selection of equations is restrained by the landslide failure mode and the water body. Due to the complexity of the surge, each calculation method needs to meet certain assumptions. For example, the foreign empirical calculation method assumes that surge is a one-way flow. In practical engineering, except for a small part of rock and soil mass falling vertically, most of the unstable sliding bodies were oblique sliding along the coastline, and the fluctuation of waves is mostly dynamic, which cannot be linearly superimposed. In addition, in order to simplify the calculation equation, some researchers assume that the problem of landslide surge is a two-dimensional plane problem, ignoring the influence of landslide thickness and scale on landslide surge. Furthermore, some researchers introduce the concept of centroid or rigid body and regard the water-entry rock soil as a complete block. However, in the actual process, these landslide bodies are often deformed or even broken, ignoring the influence of internal parameters will cause large errors in the prediction of some landslide surges. Moreover, the interaction between sliding body and water body is complex, which involves the fluid mechanics, rock mechanics and kinematics, while the influence factors of resistance such as fluid viscous force are often insufficiently considered. Therefore, it is considered that the continuity of surge calculated by empirical equation method is poor, which cannot well predict the influence of landslide failure process and wave evolution on surge disaster. Although the research on landslide surges has a long history, there are still some difficulties and problems.

5.2. Physical Model Test Method

In order to simulate the complexity of geological problems and solve the problem of theoretical analysis, scholars use a physical model test to study problems, but the physical model test method also has some difficulties and problems. The physical simulation method is based on the similarity theory to replicate the landslide body and water body in scaled dimension. This method can directly observe the wave body shape and the whole landslide surge formation, propagation and even climbing process. It is a relatively intuitive and reliable research method. However, the preparation period is long and requires a lot of labor and material resources. Mostly, the physical model test is generally aimed at a certain case, so it is only applicable to a single case or phenomenon, resulting in poor versatility. Meanwhile, there are many influencing factors of landslide surge; to summarize the variation law from the model test is the focus and difficulty of the research, and the influence on the size effect is not clear at present. Therefore, determining the appropriate scale is also a key point of the model test.

5.3. Numerical Method

The numerical simulation method can solve the problems of poor generality and the high cost of the physical model test. The numerical analysis method is a kind of flexible and intelligent solution method based on the continuous development of mathematics and computer science, which is low in cost and easy to control and can better replicate the whole process of landslide surge. In the early time, the numerical calculation is mostly for simplifying the complex multi-phase fluid–solid coupling problem into the unidirectional channel flow problem after determining the scale of the landslide body and the water-entry speed and then using the Saint-Venant equation to determine the boundary conditions, so as to calculate the simulation results. However, assumptions are too idealized to attain precise results. With the development of computational fluid dynamics, the numerical analysis method begins to be applied in solving the mathematical problems of initial conditions and surrounding boundary conditions. However, due to the complexity of the actual situation, researchers often question the accuracy of the obtained initial conditions and surrounding boundary conditions. Therefore, the numerical simulation method is mostly used as an auxiliary fitting method, which needs to be verified by other methods.

6. Conclusions

At present, the study of landslide surge cannot clearly include all factors. In the case of complex influencing factors, different research methods have certain shortcomings. This section summarizes and forecasts the landslide surge from three perspectives: theoretical analysis, a physical model test and numerical simulation.

6.1. Theoretical Analysis Method

The generation stage of surge is essentially the process of transforming the potential energy of the landslide into wave energy [87]. A landslide surge is highly nonlinear, high-order and complex. The energy conversion rate is not only related to the initial position of the landslide but also to the geometric shape, motion state, water boundary conditions, water depth and other factors of the landslide. Energy conversion rate affects the magnitude and scope of the disaster. At present, there is little research on energy conversion, and more research on landslide surges is needed in the future. In addition, the propagation and attenuation of landslide surge are hotspots of current research. However, it mainly focuses on the spatial attenuation law of wave amplitude or wave height along the radial direction at present and rarely involves the change of surge with time. In fact, the attenuation stage of surge has both space attenuation and time attenuation. The study of the spatial attenuation law is helpful to determine the spatial range of the disaster. The attenuation law in time dimension can provide theoretical guidance for early warning and prevention of the disaster.

6.2. Physical Model Test Method

At present, the physical model test of landslide surge mainly simulates block landslide and granular landslide, but there are a lot of rock landslides in the reservoir slope. The broken rock mass is neither a block model nor a granular model, so it is necessary to study this type of landslide surge. In addition, Through the analysis of the physical model of the landslide, it can be seen that the current research mainly considers the density, saturation and water content of sandstone to design the landslide model and pays less attention to mudstone. However, the particle size of mudstone is relatively small, and the water absorption is good; it is easy to soften in water and become discrete or break during the sliding process. Therefore, more attention should be paid to the physical model test of the mudstone landslide in the future.

6.3. Numerical Method

Although the development of computing technology and the computer has made it possible to use the numerical simulation technology of the N-S equation to study the landslide wave, the complex model and the decomposition, collision and deformation of complex rock and soil mass cannot be fully considered. At the same time, using the numerical simulation technology of the N-S equation to simulate requires too much computer performance and time. Therefore, a breakthrough should be made in the calculation equation and computer performance of the numerical simulation of landslide surge in the future.

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