Comparative study of empirical analysis and numerical simulation for far-field propagation of tsunamis caused by landslides

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Abstract. Landslide tsunamis can have a significant impact on the areas where they are generated and propagate. The far-field propagation of landslide tsunamis in river-type reservoirs is generally calculated using empirical formulas. By utilizing a landslide body in the Three Gorges Reservoir of the Yangtze River, a three-dimensional landslide tsunami numerical model was established based on the FLOW-3D computational fluid dynamics software. The model simulates and analyzes the propagation patterns of landslide tsunamis in real rivers and compares them with commonly used empirical analyses of landslide tsunamis. It also discusses the issues with empirical formulas in practical engineering applications and offers some suggestions.

1 Introduction

Landslides along the banks of reservoirs can lead to instability and collapse, causing the landslide body to impact the water body at a certain speed and generate huge tsunamis. Landslide tsunamis are secondary disasters of landslides, which occur when the landslide body slides into rivers, lakes, and seas, converting the energy carried into large waves in the water body. The disaster caused by tsunamis in the areas where they are generated and propagated can be extremely significant, sometimes even exceeding the landslide itself.[1-2]

Research on landslide tsunamis has attracted widespread attention and importance from scholars since the 1963 Vajont Reservoir landslide tsunami in Italy and the 1961 Tuoxi Reservoir landslide tsunami in Hunan, China[3]. Scholars at home and abroad have achieved remarkable results in the study of landslide tsunamis. A representative achievement is the empirical formula proposed by Huang and Dong in 1983, which is still widely used in the engineering field[4]. With the development of new technologies, numerical simulation is currently a commonly used method for studying the characteristics of landslide tsunamis, in addition to theoretical analysis and physical model experiments. At present, the numerical simulation methods for landslide tsunamis are mainly based on the numerical simulation of the N-S equation, and the simplified rigid block sliding simulation is the main focus. There

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is less discussion and analysis comparing the three-dimensional numerical simulation of actual landslide tsunamis with empirical formula calculations[5-6].

This paper establishes an actual three-dimensional landslide tsunami numerical model based on the FLOW-3D computational fluid dynamics software, simulating and analyzing the characteristics of landslide tsunami propagation in complex river boundaries after the landslide body enters, and comparing it with empirical formula calculations. Analyzing the differences between the two is of great significance for further revealing the propagation characteristics of landslide tsunamis and their disaster prevention and control.

2 The characteristics of the landslide

The Wildcat landslide body is located about 17 km upstream of the Three Gorges Dam, with a slope running from east to west. The maximum elevation of the mountain top is about 1300 m, and the Yangtze River water level at the foot of the slope is 135 m, with a relative height difference of about 1000 m. The front edge of the landslide body is arc-shaped, about 600 m wide, and the rear edge is elliptical, with an elevation of 410-450 m, 190 m wide, and both sides are naturally formed gullies, 800 m long; it presents a fan shape from the plane. The area is about 0.35 km2, with an average thickness of about 50 m, and a volume of 1700×10^4 m^3. The overall view of the landslide body is shown in the following figure.

Fig. 1. Overall View of the Wildcat Landslide Body.

The overall sliding block is a slope soil body, with a steep cliff behind the slope, the slope angle from the front of the slope to the river surface is 30-35 degrees, the middle part of the sliding block is relatively gentle, with an average slope angle of 13-15 degrees, and the rear end of the landslide body is generally 5-8 degrees. The river channel where the landslide is located is approximately 120 degrees, and when the reservoir water level is 135 m, the river width is about 600 m, and the riverbed height is 27 m. When the reservoir water level is 175 m, the river width is about 800 m. The characteristics of the Wildcat landslide are shown in Table 1.

Table 1. Characteristics of the Wildcat Landslide.

Parameter Name	Reservoir Water Level (m)	Gravity Acceleration (m/s^2)	Landslide Body Water Entry Length (m)	Landslide Body Water Entry Width (m)	Landslide Body Water Entry Thickness (m)	Maximum Velocity During Sliding Body Water Entry (m/s)	Water Depth (m)	Sliding Surface Inclination Angle (°)
Numerical Value	145	9.8	550	400	30	21.3	65	22

3 Numerical simulation

3.1 Wildcat landslide tsunami numerical model

The three-dimensional landslide tsunami model (hereinafter referred to as "this paper's model") is constructed using the FLOW-3D software. FLOW-3D is a Computational Fluid Dynamics (CFD) simulation software that discretizes and solves the Navier-Stokes control equations set during the motion process, thereby transforming actual fluid dynamics problems into a process of solving equations. This allows for numerical simulation and analysis of fluids. By selecting the correct parameters, FLOW-3D numerical simulation can effectively demonstrate the evolution process of geological disasters, providing theoretical basis and technical support for quantitative risk assessment and disaster prevention and mitigation engineering of landslides, debris flows, and other geological disasters [7-9].

During the simulation process, a moving solid model is primarily used to simulate the sliding, while a turbulence model and a gravity model are introduced as auxiliary models to make the simulation of the landslide body's sliding more realistic. The fluid control equation is the incompressible Navier-Stokes equation for fluid motion, and the standard RNG k-ε model is used to describe the characteristics of fluid turbulence. The GMO model controls the movement of the landslide body, and the TruVOF technology captures the undulations and splashes of the water surface. By adjusting the friction coefficient and the collision coefficient in the GMO model, the sliding, impact with the water surface, and the bottom touch states of the landslide body can be changed to obtain accurate tsunami results.

In the FLOW-3D software, the boundary conditions set during the simulation process are as follows: the upstream and downstream of the river channel use a free outflow boundary, and a pressure boundary is used in the Zmax direction, with all other boundaries being fixed boundaries (wall). To explore the propagation of the tsunami in the river channel, a measurement point (red point in the figure) is set every 500m along the central axis of the river channel, with the main monitoring target being wave height. The landslide and river channel model are shown in the figure.
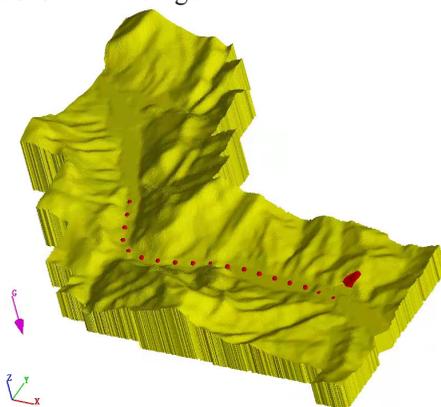

Fig. 2. Overall view of the wildcat landslide body.

3.2 Numerical simulation results

The calculation results are shown in the figure below, where the free surface elevation in the diagram is 2800 meters.
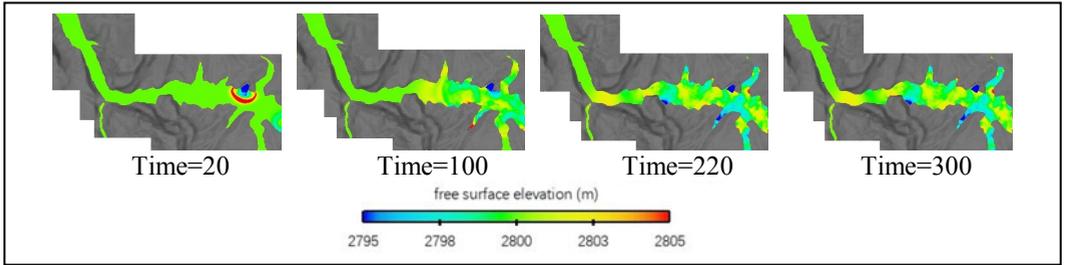
Fig. 3. Landslide Tsunami Propagation Diagram.

4 Comparative analysis of empirical calculation and numerical calculation

4.1 Empirical formula

Currently, it is quite challenging to analytically solve the problem of landslide tsunamis. Typically, the analytical solution formulas are empirical formulas derived from existing measured data. These formulas are mostly used to predict wave height, calculate the sliding speed of the landslide body, and estimate the run-up height of the tsunami, and are generally summarized as empirical formulas.Huang and Dong, in 1983, based on a large amount of experimental data and actual cases, proposed an empirical formula for calculating landslide tsunamis from the Hydraulic Research Institute, which is still widely used for tsunami prediction today.

$$h = Ku^n v^{0.5}/2g \qquad (1)$$

In the formula, u is Landslide sliding speed (m/s); n=1.3∼1.5; v is Landslide volume (ten thousand m³); K is Comprehensive influence empirical coefficient related to the distance from the landslide point.
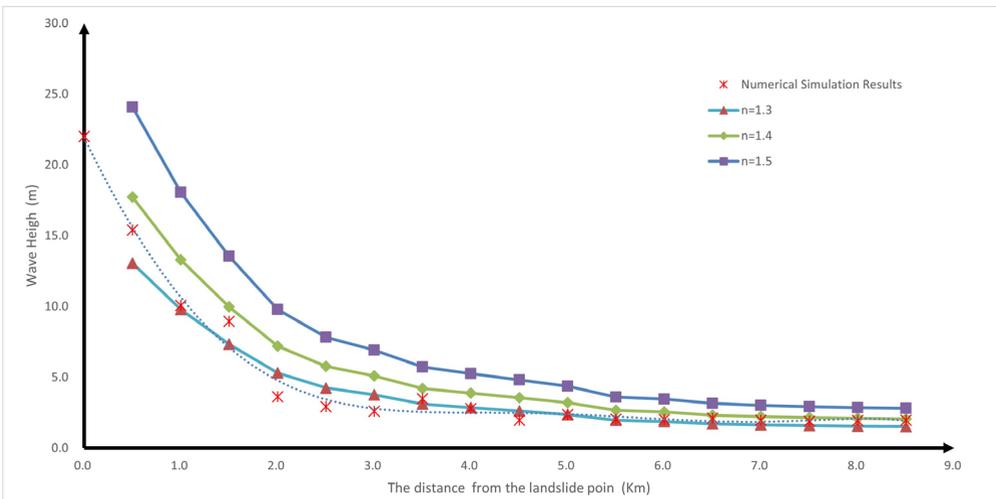
4.2 Comparative analysis

Fig. 4. Comparison Chart of Calculated Tsunami Wave Heights.

Table 2. Comparison Table of Calculated Tsunami Wave Heights.

| Distance (km) | Simulated Wave Height (m) | Empirical Formula(Hydro-Science Institute) | | | | | |
| | | n=1.3 | | n=1.4 | | n=1.5 | |
		Wave Height(m)	Relative Difference	Wave Height(m)	Relative Difference	Wave Height(m)	Relative Difference
0.5	15.40	13.06	-15.20%	17.73	15.15%	24.07	56.35%
1.0	10.06	9.79	-2.65%	13.30	32.18%	18.06	79.48%
1.5	8.95	7.35	-17.92%	9.97	11.45%	13.54	51.33%
2.0	3.63	5.30	46.05%	7.20	98.30%	9.78	169.26%
2.5	2.92	4.24	45.18%	5.76	97.13%	7.82	167.67%
3.0	2.60	3.75	44.47%	5.10	96.16%	6.92	166.35%
3.5	3.48	3.10	-10.84%	4.21	21.06%	5.72	64.38%
4.0	2.79	2.86	2.25%	3.88	38.84%	5.27	88.52%
4.5	1.97	2.61	32.57%	3.55	80.00%	4.81	144.41%
5.0	2.36	2.37	0.41%	3.21	36.33%	4.36	85.11%
5.5	2.05	1.96	-4.27%	2.66	29.98%	3.61	76.49%
6.0	2.02	1.88	-7.22%	2.55	25.98%	3.46	71.05%
6.5	2.11	1.71	-18.97%	2.33	10.03%	3.16	49.40%
7.0	1.96	1.63	-16.87%	2.22	12.88%	3.01	53.27%
7.5	1.89	1.59	-15.82%	2.16	14.30%	2.93	55.19%
8.0	1.95	1.55	-20.59%	2.11	7.83%	2.86	46.41%
8.5	1.97	1.52	-22.96%	2.06	4.60%	2.80	42.03%

The analysis indicates that:

(1) The empirical formula calculations are generally consistent with the numerical simulation results in terms of overall trend, with the simulated wave height gradually decreasing as the distance increases. When n is taken as 1.3, the empirical wave height is generally lower than the simulated wave height, whereas when n is taken as 1.4 and 1.5, the empirical wave height is generally higher than the simulated wave height, and the increase in the parameter n leads to an increase in the difference between the empirical and simulated wave heights.

(2) The numerical simulation results are closest to the calculated results when n is taken as 1.3, with the smallest absolute differences, but most of the relative differences are negative, indicating that the empirical wave height generally underestimates the simulated wave height. When n is taken as 1.4 and 1.5, the absolute value of the relative differences also increases with the increase of n, indicating that the empirical wave height increases with the increase of n, and most of the relative differences are positive, indicating that the empirical wave height is generally higher than the simulated wave height.

(3) In the table, we can see that within the 2-3 km distance range, the relative difference between the empirical and simulated wave heights is the greatest. When n is taken as 1.3, the difference is 46.05%, when n is taken as 1.4, the difference is 98.30%, and when n is taken as 1.5, the difference is as high as 169.26%, which is a significant outlier. After a distance of 5.0 km, the relative difference between the empirical and simulated wave heights is relatively small. The smallest relative difference, when n is taken as 1.3, is only 0.41%. It is indicated that empirical formulas have larger errors in the early stages of tsunamis propagation and smaller errors in the later stages, making empirical formulas

more advantageous for calculating the propagation characteristics of tsunamis at greater distances.

5 Conclusion

Based on the computational fluid dynamics software Flow-3D, a numerical simulation of the propagation process of landslide tsunamis in real environments was carried out. The computational results are in general agreement with the results calculated using empirical formulas from the Water Science Institute. This demonstrates that the Flow-3D software is a reasonable tool for studying the propagation process of landslide tsunamis.

The analysis indicates that the wave heights calculated by empirical formulas generally conform to the basic laws of landslide tsunamis. However, empirical formulas are mostly based on the fundamental theory of landslide tsunamis and derived from experiments in rectangular flume models and semi-infinite water bodies. They may be overly simplified and ignore factors such as the river channel terrain, cross-sectional shape, and degree of curvature where the tsunamis occurs in actual cases. Therefore, their applicability to landslide tsunamis in complex river channels is limited. As a result, in practical applications, the key parameter n in the empirical formulas must be calibrated through experiments.

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