# Propagation of landslide induced impulse wave in channel type reservoirs

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**Abstract**. The propagation characteristics and parameter sensitivity of the landslide induced impulse wave in practical channel type reservoirs are investigated in this study. The two-dimensional Saint-Venant equation and dry-wet boundary treatment method are used to simulate the wave generation and propagation processes in real reservoirs. In order to better reproduce the initial wave, a matching technique of initial wave between nearfield and far field simulation is implemented, while the nearfield wave generation processes are simulated based on full Naiver-Stokes equation. A real landslide induced impulse wave event is simulated with this technique and the propagation characteristics and parameter sensitivity are investigated. The simulation results and comparison between different cases indicate that the longitudinal shape of the channel-type reservoir is a crucial factor for propagation. Classical engineering methods which ignore this factor might produce improper estimation of the max wave height.

## 1. Introduction

The landslide induced impulse wave (LIIW) is a common but destructive disaster which happens generally in reservoirs and sea coast. In the mountainous area, many steep slopes locate at the bank of reservoir. Numerous events could trigger slope failure of these slopes, thereby massive landslide body might run into the water with high speed and thus cause destructive huge wave which will propagate to the upper and lower reaches in the reservoir. Comparing with LIIW in the basin-type reservoir, the LIIW in the channel-type reservoirs might be more danger as wave energy density of the latter is larger than the former at the same far field site.

Heller and Hager (2010) [1] developed two models for both 2D LIIW and half-plane 3D LIIW. Their estimation is directly based on impact parameters and the distance between observation site and the impact site without explicit discrimination of the generation and propagation processes. In fact the generation process and the propagation process of LIIW are controlled by different physical mechanism and thus can be very different. The kernel mechanism of the wave generation is the energy transport and transform between landslide body and the water flow. Different energy magnitude and distribution lead to different wave form, while the energy dissipation in the inner generation zone is so strong that wave cannot sustains. The Naiver-Stokes equation instead of any depth averaged equation should be used to represent this process, as the velocity in the height direction could not be ignored and significant energy is consumed in the wave generation processes. As for the propagation process, the key mechanism is the wave dissipation and reflection in reservoirs with complex boundaries, while the energy dissipation in this process is much smaller than it of the generation process. Thus, the depth averaged theory such as 2D Saint-Venant equation could be applied in this problem. As the spatial size of interested area for the wave propagation calculation is at least one order larger than it of wave generation calculation, a united method of N-S equation based simulation for wave generation and S-V equation based simulation for wave propagation is the best choose for the whole problem except some special events.

## 2. Numerical Model

A united model of 3D N-S equation based SPH model and 2D S-V equation based model is developed in this study. The generation process is modeled with the 3D SPH method while the wave propagation is modeled with 2D S-V equation based model. The latter is developed on the open source project Basilisk by Popinet [2]. The two models are connected by the initial wave height at a specific position where the waves become steady and most wave energy could propagate. In this study, this position is about two times of the maximum water depth away from the rim of the landslide body.

### *2.1. Simulate wave generation with SPH method*

Using the weak compressible SPH method, the Naiver-Stokes equation could be transform to the following discrete form represented on particles:

$$\frac{d\rho_a}{dt} = \sum_b m_b \left(\boldsymbol{v}_a - \boldsymbol{v}_b\right) \cdot \nabla_a W_{ab} \tag{1}$$

$$\frac{d\boldsymbol{v}_a}{dt} = -\sum_b m_b \left( \frac{P_b}{\rho_b^2} + \frac{P_a}{\rho_a^2} + \Pi_{ab} \right) \nabla_a W_{ab} + \boldsymbol{g} \tag{2}$$

where all information (density $\rho$, pressure $P$, velocity $v$ and mass $m$) of particle "a" could be calculated by integral of nearby particles. The $W_{ab}$ is kernel function act as weighting function, and the $\Pi_{ab}$ is artificial viscosity term representing fluid viscosity. Detailed information of SPH method and its application on LIIW problem could be found in Shi et al.'s papers [3,4].

### *2.2. Simulate wave propagation with Basilisk*

Two-dimensional Saint-Venant equation could be written in the following conservative form:

$$\frac{\partial q}{\partial t} + \frac{\partial f(q)}{\partial x} = S \tag{3}$$

$$q = \begin{pmatrix} h \\ hu \\ hv \end{pmatrix}, \quad f(q) = \begin{pmatrix} hu & hv \\ hu^2 + \frac{1}{2} gh^2 & huv \\ huv & hv^2 + \frac{1}{2} gh^2 \end{pmatrix}, \quad S = \begin{pmatrix} -\partial Z_b / \partial t \\ gh(S_{bx} - S_{fx}) + hv_t \Delta u \\ gh(S_{by} - S_{fy}) + hv_t \Delta v \end{pmatrix} \tag{4}$$

where $h$ is the water depth, $z$ is the elevation of reservoir bottom, $\eta = z + h$ is the elevation of water surface, ($u$, $v$) is the horizontal averaged velocity of flow, g is gravity, the first row of $q$ and $f(q)$ are from continuity equation, the second and third row are from moment conservation equation, the drag from the bottom is consider as source term of equation (3), and take the following form:

$$S = -\frac{n^2 \left\| \vec{U} \right\|^2}{h^{4/3}} \vec{U} \tag{5}$$

where $n$ is the Manning coefficient, and $\vec{U}$ is the velocity vector.

The adaptive octree mesh refine technique of Basilisk project is employed in this study. Mesh in any region which needs accurate wave simulation (such as shallow area, steep wave and wave run-up) will be refined to achieve good accuracy. While mesh in those regions that do not need detailed simulation will be coarsened to cut down the computational cost and reduce numerical dissipation.

Compared with classical method, this adaptive mesh refine method could achieve the balance between accuracy and computational cost.

## 3. Case study

Two LIIW cases with real reservoir configuration are studied. The first one is the Huangtian LIIW event in which the longitudinal shape of the channel is curvy and furcate. The second one is a presumed LIIW event happens in a real straight channel-type reservoir, which is a good comparison for the former.

### *3.1. Huangtian LIIW event*

Huangtian LIIW is a real event happened in 20th Jul, 2009. Huangtian landslide which located in Xiaowan reservoir is about 7.5 Km away from the Xiaowan dam. Stormed by a very heavy rain, the Huangtian slope failed and about 1 million cubic meters slid into the reservoir, induced 30 meters high huge wave. A wave height about 2m is recorded at the survey site located just in front the dam. The DEM of the calculation area is shown in Fig. 1.

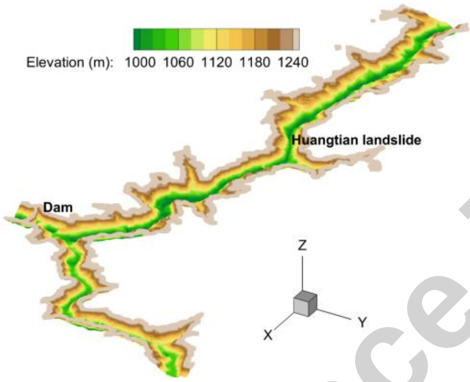


Figure 1. DEM model of Huangtian LIIW simulation

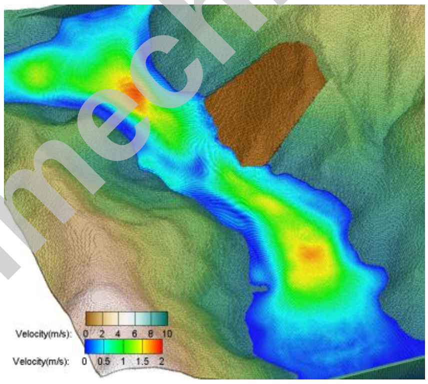


Figure 2. Snapshot of wave generation process colored by velocity

*3.1.1. Wave generation simulation.* Shi et al. (2015) [3] had simulated the generation process of this LIIW event with SPH method. The length of the calculation area is about 14 times of water depth, and the wave hydrograph at the 2 times of water depth away from the rim of landslide is recorded. The recorded wave parameters such as wave height and wave period are used for wave propagation calculation. Due to the limit of space, here we just show one snapshot of the simulation (Fig. 2). More details on wave generation could be found in Shi et al.'s paper.

*3.1.2. Wave propagation simulation.* The simulation zone (19262m × 8030m$^2$) is as large as 3 times of the distance between the Huangtian landslide and the dam. Thus the whole LIIW propagation processes could be simulated while no wave reflection at the upper and lower boundaries will influence the interested area. We use the digital elevation model data from ASTER v2, of which resolution is 30m, to represent the simulation area. The most coarsen mesh is about 75m and the finest mesh is about 4.7m. The maximum total elements in the simulation is about 2 million. The simulation start from the generation of the initial wave and last for ten minutes while the time step is 0.02s. Each case cost about 12 CPU hours in the super computer of "Yuan", Chinese Academy of Sciences.

All physical parameters are set according to the real situation, while two main empirical parameters to be determined are Manning drag coefficient and vortex viscosity. Considering the shape of channel cross section is like "V", the contribution of the side wall on the wet perimeter is significant. Also, the numerous junction points and large scale roughness will result larger drag comparing with normal channels. Thus the Manning coefficient is set to 0.06 which is generally suit for gravel rivers. The determination of vortex viscosity is very empirical as different studies often use very different values. Actually, this parameter is related with the mesh size. Il Won Seo et al. (2014) [5]

choose the value of 5e-3 by calibrating with small scale laboratory flume experiment. If we use the Smagorinsky 2D vortex viscosity relationship to scale this value:

$$\upsilon_t = (C_s\Delta_g)^2\sqrt{(\frac{\partial u}{\partial x})^2+(\frac{\partial v}{\partial y})^2+\frac{1}{2}(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x})^2} \quad (6)$$

we can obtain the value of 94 for vortex viscosity, which is a proper choice as it is close to empirical values that the previous study has used.

A typical simulation snapshot is shown in Fig. 3 coloured by water elevation. In Fig.3, we can see that the wave is propagating to the upper and lower reaches, while the wave height at the lower reach is significantly smaller than it of upper reach. It is clear that a part of wave energy is transport to a branch gully instead of going to the lower reach. This phenomena could also be seen in Fig.4 which shows the time evolution of water elevation at specific points. The wave height of leading wave is dramatically decreasing along with the channel, drop to 1.7m at the crossroad, and then increase by swelling effect to 2.0m in front of the dam, which is consistent with the observation data. Also the decrease rates at the branch section and the turning section are obviously larger comparing with other sections.

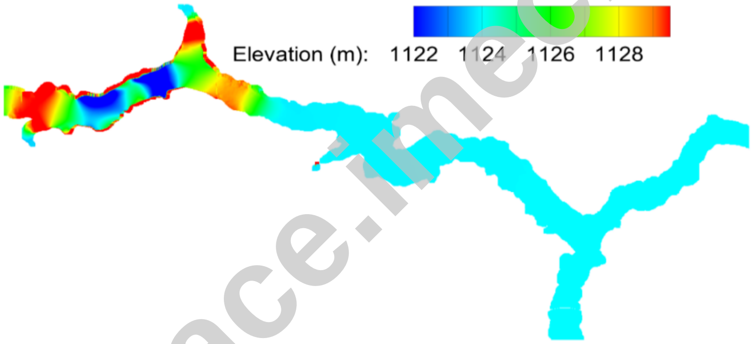

Figure 3. Snapshot of wave propagation process coloured by water elevation

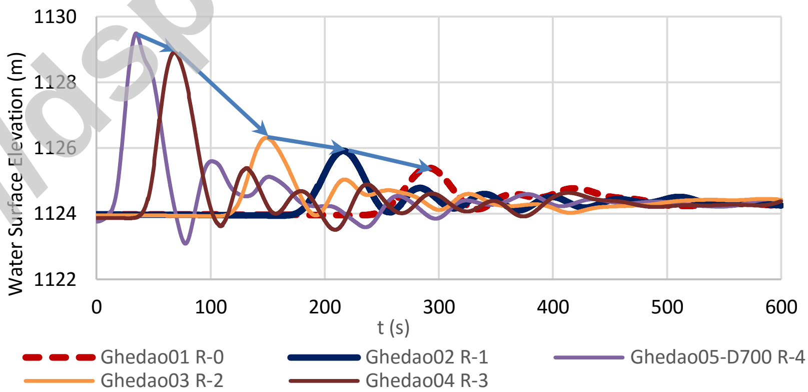

Figure 4. The water elevation evolution at specific points

### *3.2. A straight channel-type reservoir case*

To study the influence of the turning and the branch on the propagation of the LIIW. We found a real straight channel-type reservoir which is similar to the Xiaowan reservoir in many aspects except the longitudinal shape. In this case, the influence of tuning and the branch is very small and the dam axis direction is perpendicular to the wave incidence direction.

Two snapshot on water elevation of the initial and medium stages of wave propagation are shown in Fig. 5, respectively. It is clear that the wave energy is mainly dissipated in the generation zone while the wave energy which could propagate to the downstream is relatively small comparing with the initial wave. Also, as the channel is rather straight, the wave height does not decrease very much in the channel.

Besides, as the dam axis is perpendicular to the longitudinal direction of the channel, the wave will run-up at the dam slope and all wave energy will accumulate which might result very huge wave at the dam site. We could also see this phenomena in the quantitative hydrograph of wave height at different location in the reservoir as shown in Fig.6.

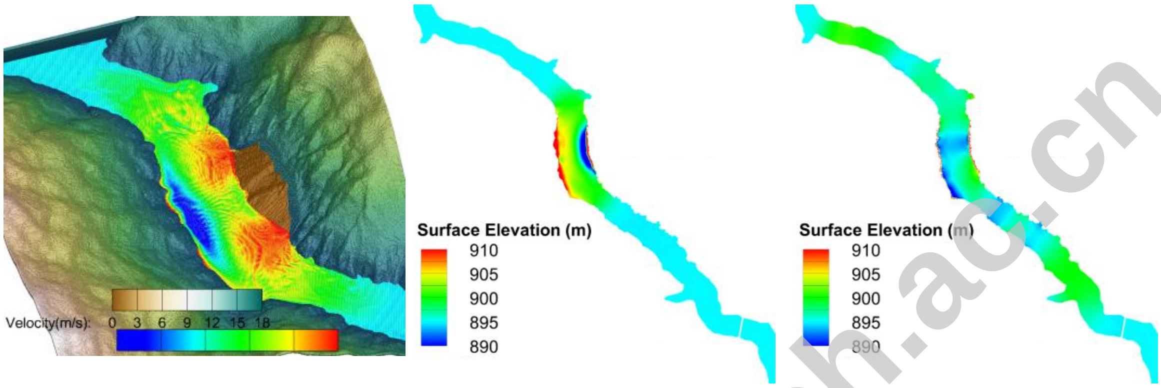


Figure 5 Snapshots of the simulated wave generation and propagation processes

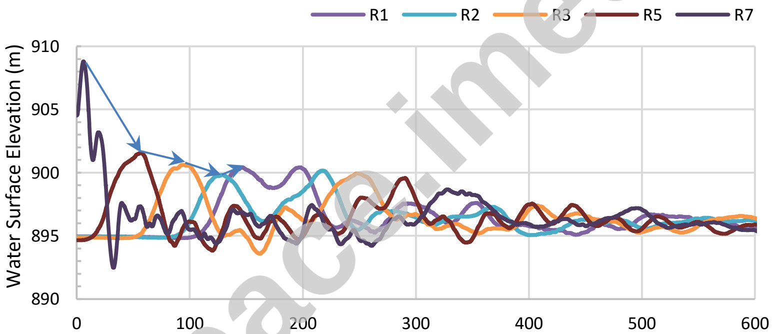


Figure 6 Water elevation at the specific locations in the reservoir

## 4. Discussion on parameters sensitivity

The wave propagation calculation based on two empirical parameters: the Manning roughness and the vortex viscosity. Here we discuss the sensitivity of those two parameters based on the latter case study.

To discuss the sensitivity of the Manning roughness, four values of Manning roughness (0.01, 0.0.3, 0.06 and 0.09) are chosen for comparison. We can see in Fig.7 that the result is not sensitive to the value of the Manning roughness.

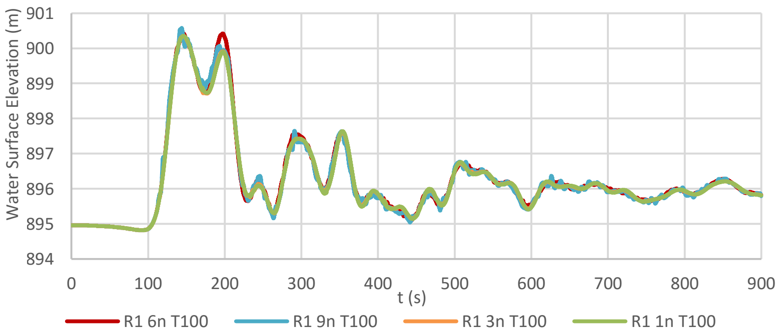


Figure 7 Parameter sensitivity analysis of the Manning roughness

To discuss the sensitivity of the vortex viscosity, three values of vortex viscosity (70,100 and 130) are chosen for comparison. The value of 100 is the same as the case study and the other two is ±30% of the parameter value. Figure 8 shows the hydrograph at the R1 point which locates at the front of the dam. We can see that the sensitivity of the result to the parameter value is medium. A change of ±30% of the value will result about 5% variation of wave height. That is because the vortex viscosity mainly represents the two dimensional moment transport and dissipation which definitely influence the wave height, however as the water depth in this case is very large and the large velocity zone in real 3D situation is always located at the surface, the depth averaged moment would not be too sensitive to the vortex viscosity.

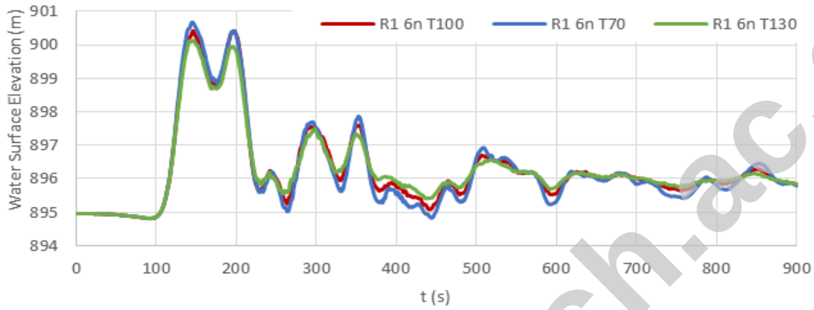


Figure 8 Parameter sensitivity analysis of the vortex viscosity

## 5. Conclusion

The propagation characteristics and parameter sensitivity of the LIIW in practical channel type reservoirs are investigated in this study. It is found that the united method of 3D SPH simulation for wave generation and 2D S-V equation based simulation, along with a matching technique of initial wave between nearfield and far field simulation could provide better result on LIIW simulation. A real LIIW event and a presumed LIIW event based on real configuration are simulated with this technique. The propagation characteristics for both LIIW events are discussed.

We found that the longitudinal shape of the channel-type reservoir, such as turning and branch gully, is crucial factor controlling the propagation of LIIW. Classical engineering methods which ignore this factor might produce improper estimation of the max wave height. The parameter sensitivity of the Manning roughness is weak as the water depth is generally very large. While the parameter sensitivity of the vortex viscosity is medium and should be carefully treated.


## Acknowledgements

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