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Impulse water waves generated by snow avalanches

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ABSTRACT: Retaining dams devoted to artificial snow production, are most of the time located in the vicinity of steep slope areas and may be threatened by snow avalanche impacts. To assess the risk of over toppings (overflows), the estimation of the consequences of an avalanche impact in terms of wave magnitude is required. Due to the low density ratio between the snow and the water, the extrapolation of available scaling laws, established for high density ratios (landslides and debris flows), may lead to a misestimating of the wave characteristics. To extend the existing scaling laws in the low density ratio domain, multiphase numerical simulations are conducted. The objective is to investigate the nature and the magnitude of the water wave generated by the impact of a natural fluid of low density. Both vertical and horizontal impacts are considered and their effects are studied. The dependence of the wave amplitude on the density ratio is highlighted. The main conclusions drawn up from this study are the following. The wave amplitude is an exponential function of the avalanche density. This function is very steep for low density ratios. For density ratios higher than 0.5, the trend is much smooth and tends towards the scaling laws established for landslides.

KEYWORDS: impulse water waves, snow avalanches, mountain lakes.

1. INTRODUCTION

The number of skiers in ski resort has increased significantly during the last decades. Consequently the water household used increased proportionally. In intermediate altitudes mountainous areas, the global warming disturbed significantly the snow precipitation cycles making snow availability during winter highly aleatory. To guarantee the availability of the snow during the winter season and notably during winter holidays, the ski resorts use artificial snow to increase the amount of snow available for winter sports such as skiing or snowboarding.

To these ends, ski resorts develop retaining reservoirs to collect and store the water during summer to satisfy the customers' needs both for domestic water and for snow. Several reservoirs were built, some of them are located in, or close enough, to avalanche run-outs and thus are threatened by avalanche hazard (see figure 1). Downstream of some reservoirs, economic and human issues are threatened by any flow of water from these lakes.

Since significant impulse water waves may be produced in a lake by the sub aerial impact of rapid mass flows (e.g landslide, debris flows or avalanches (Walder et al. 2003)), the evaluation of the magnitude of such waves is a crucial issue for public safety.

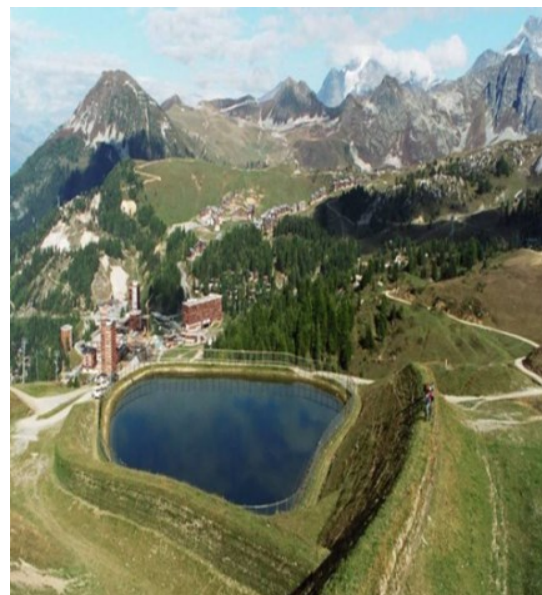


Figure 1. Water reservoir located in the run-out area of an avalanche, protected by a dike, and threatening an urbanized area located downstream, (Picture by courtesy of P. Meriaux).

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Figure 2. Photo of Pelvoux reservoir which has been emptied by an avalanche. The water has been spilled down the slope. (Picture by courtesy of S. Escande).

The magnitude of the impulse waves depends in a nontrivial way on the mass flow parameters (height, velocity and density). The density of snow avalanches varies roughly between $100 \text{ kg}\cdot\text{m}^{-3}$ and $500 \text{ kg}\cdot\text{m}^{-3}$. Applying existing formulas developed for a slide of density higher or close to the water density, may lead to an overestimation of the wave characteristics.

The question, of how the amplitude of the wave evolves with the density for mass movement of low density, emerged as an important issue both from technical and scientific perspectives. This paper tackles this question.

2. IMPULSE WATER WAVES

Impulse waves generated by sub aerial landslide were experimentally investigated by numerous authors. Several theoretical and experimental works characterized the wave features (nature, amplitude, speed). Several scaling laws were evidenced and useful relationships were obtained using small scale models. Three dimensionless numbers emerged as the main parameters. The first one is the impact Froude number $F = \frac{V_{\text{impact}}}{\sqrt{gd}}$ (the ratio of the mass movement velocity V_{impact} to the square root of the initial water depth d times the gravity acceleration g). The second number is the dimensionless slide volume, $Q = \frac{sl}{a^2}$, defined as the ratio of the slide thickness s , times the slide length l , over the square of the initial water depth. The third is the dimensionless slide density ratio $R = \frac{\rho_s}{\rho_w}$, where ρ_s and ρ_w are respectively the densities of the sliding mass and the water.

Several authors investigated experimentally the effect of various parameters describing the slide and the receiving body of water on the generated impulse waves. They studied wide ranges of the Froude number and the dimen-

sionless volume at impact. They performed several tests, and established relevant scaling relationships. In the experiments by Kamphuis and Bowering 1972 for instance, a wide range of F and Q was covered for a fixed density of the slide ($2700 \text{ kg}\cdot\text{m}^{-3}$), representing the case of a landslide. These authors reported that the wave height stabilized very quickly. The relative wave amplitude of the stable wave is a function of the dimensionless slide volume and the impact Froude number. The obtained function is given by equation 1:

$$\frac{A}{d} = F^{0.7} [0.31 + 0.2 \ln(Q)] \quad (1)$$

In the current study, we reanalyzed the set of data published by Kamphuis and Bowering 1972, using a multivariate fitting. We obtained the same dependence of Q but the index of the power function of the Froude number was found lower; 0.63 instead of 0.7.

$$\frac{A}{d} = F^{0.63} [0.31 + 0.19 \ln(Q)] \quad (2)$$

Concerning the density ratio, Zweifel et al. 2006, studied the following ranges of Froude number and dimensionless volume: $1 < F < 5$ and $0.07 < Q < 1.2$. They varied the density ratio between 0.955 and 2.64. Even if they did not explore low density ratios, they showed that the relative wave amplitude is a power law function of the density ratio R with a power index of 0.25.

3. NUMERICAL SIMULATIONS

The previous researches addressed the case of mass movements of high density ($0.9 \leq R$). To our knowledge, no previous study has addressed the case of low density ratios (i.e. $R \leq 0.5$), corresponding to the domain of snow avalanches.

As a consequence, the empirical scaling laws cannot be applied directly to predict the impulse waves a snow avalanche impact may produce in a lake. A misestimating of the wave characteristics is expected. We therefore conducted the following research, in order to establish the relationship of the relative wave amplitude as function of the density ratio for low density ratio. To this end we performed numerical simulations using a multiphase numerical computational fluid dynamics code. The numerical experiments conditions have been set as follow:

- 2d channel of 10 m long is considered, x and z are respectively the horizontal and the vertical axis,
- The water depth d is set at 0.5 m,
- The avalanche falls vertically or impact horizontally the receiving body of water, at one end ($0 < x < 0.5$),
- The avalanche is represented by a Newtonian fluid of density ρ_s and viscosity ν_s .

- The avalanche velocity is set at $4 \text{ m}\cdot\text{s}^{-1}$ leading to Froude number F of 1.78,
- Both the avalanche thickness and length are set at 0.5 m,
- The VOF (volume of fluid) method is used to track the interface between the fluid representing the avalanche and the water,
- The flows of the mixture of the two Newtonian fluids are considered turbulent and the turbulence magnitude is approximated by the simple one-equation model proposed by Spalart and Allmaras, 1994,
- The density ratio R is varied from 0.1 to 1.3 and, 13 runs are performed one per density ratio.

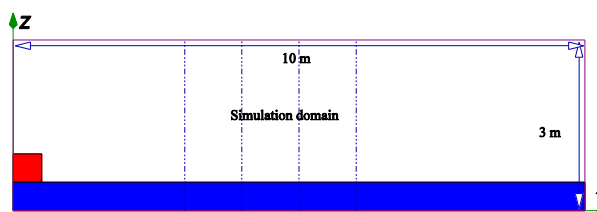


Figure 3. Main geometrical features of the numerical simulations: red area is the avalanche, the blue area is the water and the rest is the air.

4. RESULTS

For each run, the resulting wave height and the depth average velocity are measured according to time at four relative distances ($X = \frac{x}{d}$) 6, 8, 10, and 12.

As shown on figures 3 and 4, the generated wave acquires a characteristic shape after a transition period. The wave height decreases slowly with the covered distance.

Three dimensionless parameters are defined and used in this study:

- Relative wave amplitude $A(x) = \frac{\max_t |z_s(x,t) - d|}{d}$ where $z_s(x,t)$ is the water surface altitude (water depth) at distance x from the impact,
- Relative wave velocity $V(x) = \frac{v(x)}{\sqrt{gd}}$ where v is the depth average velocity of the wave.
- Dimensionless time: $T = t \sqrt{\frac{g}{d}}$

We plotted on figures 4 and 5, the dimensionless wave heights and velocities for the case of vertical impact, and for density ratios between 0.1 and 1.2.

When R increases, the amplitude and the velocity of the wave increase. The shape of the wave steepens.

For vertical impact, the wave amplitude increase is much pronounced for density ratio between 0.1 and 0.5; domain corresponding to the snow avalanche density ratio.

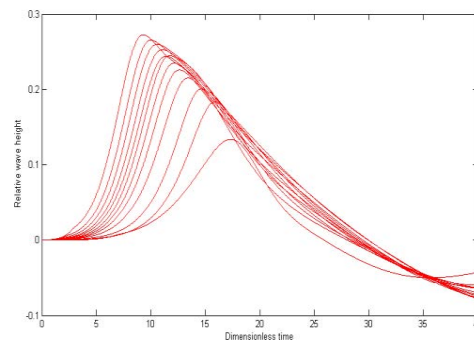


Figure 4(a), X=6

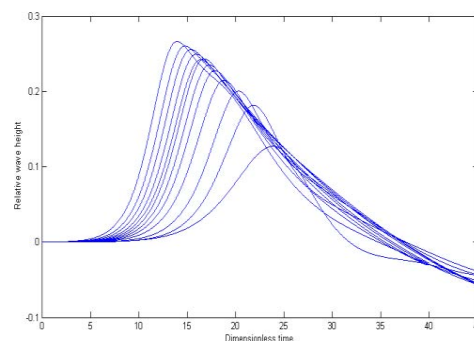


Figure 4(b), X=8

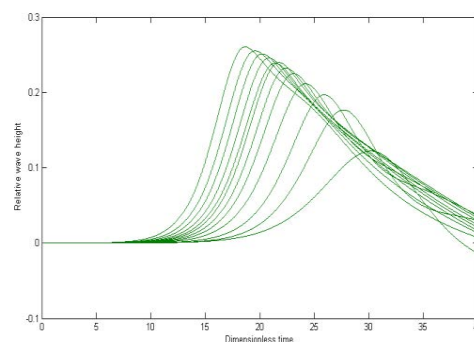


Figure 4(c), X=10

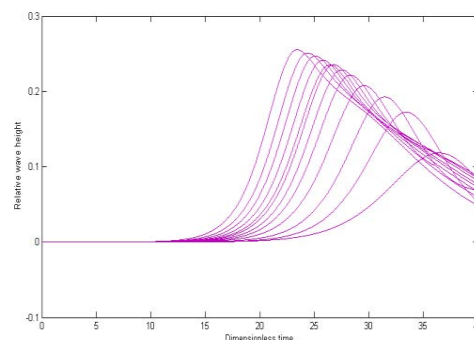


Figure 4(d), X=12

Figure 4(a,b,c,d). Relative wave height function of dimensionless time at X=6, 8, 10 and 12 for $F=1.78$, $Q=1$ and R ranging from 0.1 to 1.13 – case of vertical impact

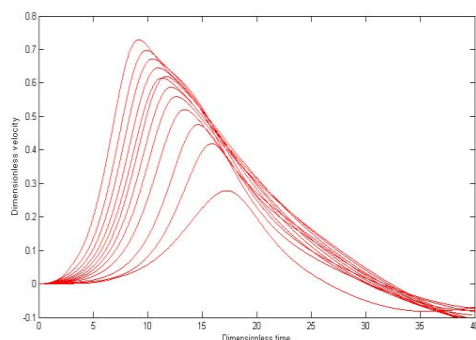


Figure 5(a), X=6

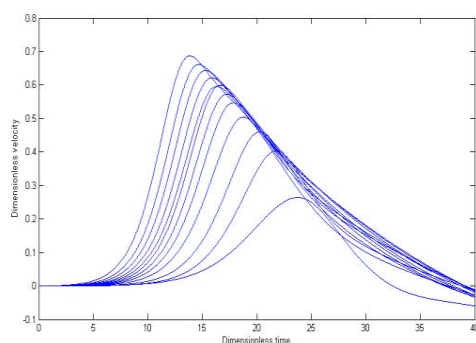


Figure 5(b), X=8

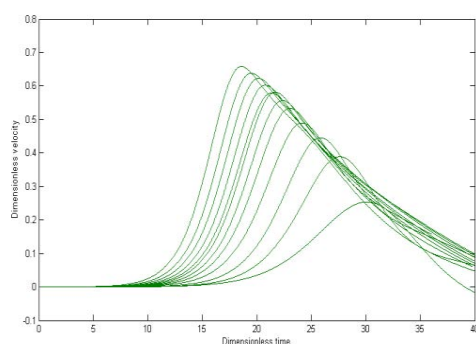


Figure 5(c), X=10

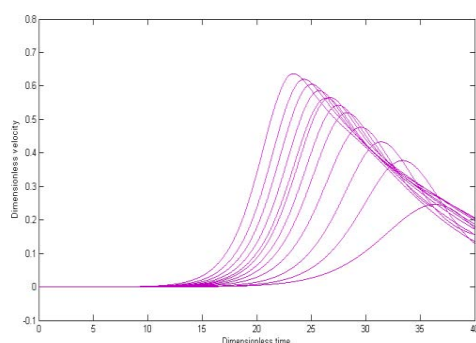


Figure 5(d), X=12

Figure 5(a,b,c,d). Wave dimensionless velocity function of dimensionless time at X=6, 8, 10 and 12 for F=1.87, Q=1 and R ranging from 0.1 to 1.13 – case of vertical impact.

Both for horizontal and vertical impact, the dimensionless amplitudes of the wave have been determined for R between 0.1 and 1.2 at four locations (X=6, 8, 10 and 12). The obtained data are plotted in figure 6.

The data obtained for the horizontal and vertical impact showed that the horizontal impact produces a wave 25% higher than the one produced by the vertical fall.

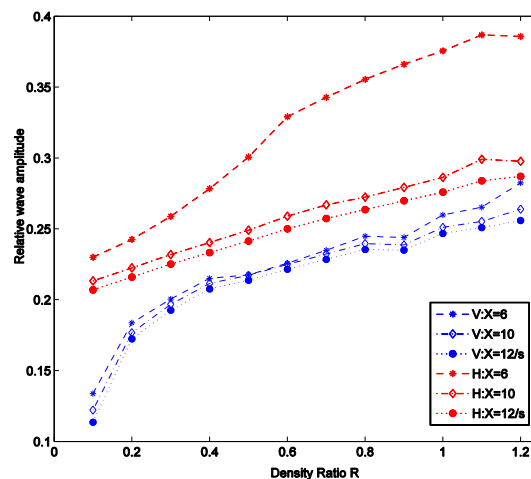


Figure 6. Relative wave amplitude function of the density ratio at three locations from the impact (X=6, 8 and 12) – Horizontal and vertical impact cases are compared.

5. WAVE AMPLITUDE AS FUNCTION OF DENSITY RATIO

The amplitude of the wave as a function of R is determined by fitting a double exponential function to the data obtained for the vertical impact. The relation obtained is written in equation 3:

$$\frac{A}{a} |_{vertical} = 0.18e^{0.33R} - 0.30e^{-14.28R} \quad (3)$$

The numerical study undertaken here, investigated densities between $100\text{kg}\cdot\text{m}^{-3}$ and $1200\text{kg}\cdot\text{m}^{-3}$. Its relevance is then demonstrated only for this range.

If the equation 3 is extrapolated to a density of $2700\text{kg}\cdot\text{m}^{-3}$, the relative amplitude found is 0.44. On the other hand, if we use the equation 2 established by Kamphuis and Bowering 1972 for a density of $2700\text{kg}\cdot\text{m}^{-3}$, the amplitude obtained with our numerical experiment conditions (Q=1 and F=1.78) is 0.47. This last, deduced from experimental data, is considered as the reference for a density of $2700\text{kg}\cdot\text{m}^{-3}$. Formula 3 underestimates the relative magnitude by only 6%. Considering that the density range for which it was established is much lower, the predictive ability of formula 3 is satisfying.

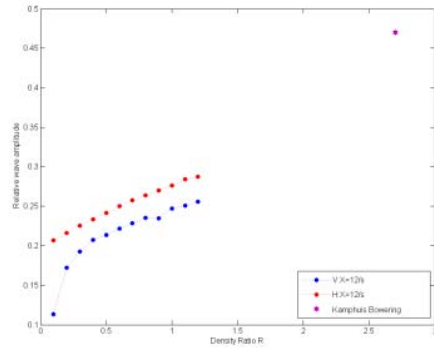


Figure 6. Relative wave amplitude as function of the density ratio (our data and Kamphuis and Bowering 1972 prediction).

The equations 3 together with the numerical data and the predicted value by equation 2 are plotted in figure 7. An extrapolation from the horizontal impact data provides more accurate estimates of the wave amplitude for density of 2700 kg.m^{-3} .

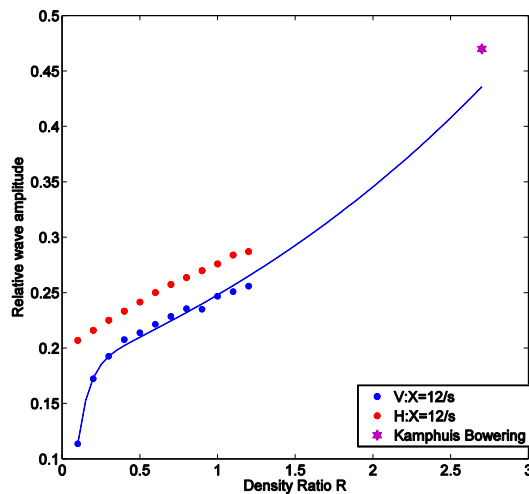


Figure 7. Stable wave relative amplitude as function of the density ratio: data and fits

The equation 3 is used to introduce the density effect in the empirical formula given by equation 2. The new expression of the relative wave amplitude is thus given by:

$$\frac{A}{d} = \frac{0.18e^{0.33R} - 0.30e^{-14.28R}}{0.745 + 0.47 \ln(Q)} F^{0.63} \quad (4)$$

To test this new formula, in addition to the data obtained by Kamphuis and Bowering and the data obtained thanks to the above numerical simulations, we performed several new numerical simulations for the horizontal impact, by varying the impact Froude number between 0.5 and 3 while maintaining the dimensionless volume Q equal to 1. We performed these simula-

tions for two density ratios: 0.5 and 1.5 (see figure 8).

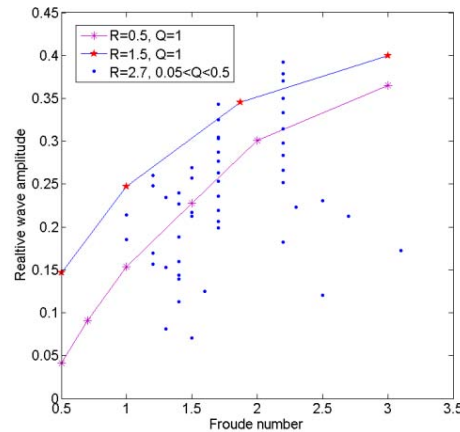


Figure 8. Relative wave amplitudes according to the Froude number including the data by Kamphuis and Bowering and the data obtained thanks to multiphase numerical simulations.

The wave amplitude predicted by equation 4 is plotted, in figure 9, as a function of the amplitude obtained experimentally or numerically. The agreement can be considered as very good since the correlation is 0.97.

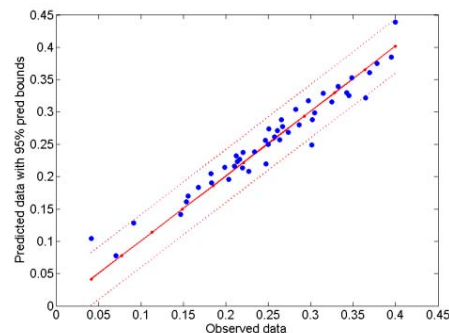
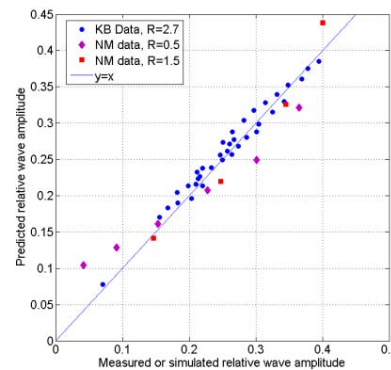


Figure 9. Relative wave amplitudes predicted by the equation 4 according to the measured or simulated ones.

6. CONCLUSIONS

A series of numerical experiments were conducted to determine the relationship governing the impulse wave amplitude generated by snow avalanches in a lake. We addressed the effects of the density ratio on the amplitude of the impulse wave generated by the impact of horizontal or vertical of a mass movement of low density. The results obtained showed an important decrease of the amplitude with the density ratio. The horizontal impact generated higher waves than the vertical impact. The numerical simulations conducted for various density ratios for fixed Froude number and dimensionless volume allowed to establish a scaling law relating the wave amplitude to the density ratio. A new formula combining the empirical formula proposed by Kamphuis and Bowering 1972 and the trend found in this study for the density ratio effect, is proposed.

Afterwards, additional numerical simulations are conducted for two density ratio (0.5 and 1.5) for various Froude numbers. The data obtained allowed to test successfully the new wave amplitude formula.

The main outcome of this paper is that the wave amplitude is an increasing function of the density ratio.

As a conclusion of this paper To conclude this paper, the obtained formula, accounting of density effect, is applied to snow avalanches. Under the same conditions of volume and impact Froude number, the wave generated by a light (respectively dense) avalanche is barely equal to 40% (respectively 55%) of the wave amplitude generated by a landslide.

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