On waves arising from dry granular collapse into water

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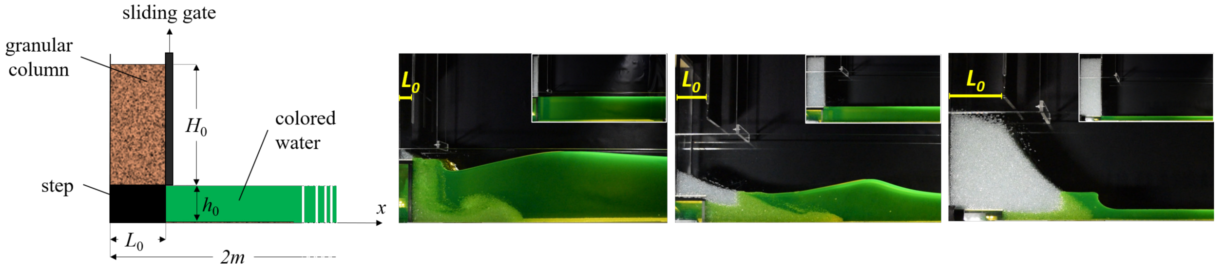
Summary Tsunami-like waves can arise from significant geological events such as the collapse of a mountain flank or a volcano into a lake or an ocean. We reproduce here this situation at the laboratory scale. The landslide is modeled by the sudden release of a rectangular granular column, which then impacts a still water layer and generates a wave. Through experiments varying both the column dimensions and the initial water height, three regimes of nonlinear waves of different shapes are reported.

INTRODUCTION

Tsunamis generated by landslides, debris avalanches or rockslides are highly destructive phenomena, with several occurrences in the last decades. Caused by major geological events involving large volumes of debris such as mountain or volcano collapses, they may result in the generation of high amplitude water waves. A well-known example is the case of Lituya Bay (Alaska, USA) in 1958 [1], when a rockslide volume of 30.10^6m^3 fell into water and produced the largest wave runup recorded in history, destroying neighbouring coastal areas up to an altitude of 524 m.
To describe the wave generation accurately, the granular nature of the falling mass needs to be taken into account [2][3]. In the present work, we investigate experimentally the collapse of granular columns into water. Various initial conditions for the column dimensions and the initial water depth are considered.

EXPERIMENTAL SETUP

Waves induced by granular collapses are experimentally reproduced using a setup described in [4]. A rectangular granular column of initial height H_0 and width L_0 is located above a water layer of height h_0, on the left-hand side of a tank of length 2 m and transverse width 0.15 m [Fig. 1 (a)]. The water is colored with fluorescein in order to enhance the contrast between water, air, and grains. Lifting the vertical sliding gate quickly releases the granular column, which impacts the water free-surface and generates a wave, as presented in Fig. 1 (b)-(d) for different initial conditions. The time evolution of the collapse and the wave is recorded with a camera, and image processing allows to extract the water free-surface and the dry and wet granular profiles. For the granular material, glass beads of diameter 5 mm and density 2500 kg.m^{-3} are used. For different column aspect ratios $a = H_0/L_0$, the water height is varied to investigate the wave generation process in a large range of global Froude number $\mathrm{Fr}_0 = \sqrt{H_0/h_0}$, between 0.5 and 4.4. This dimensionless number compares the typical vertical free fall velocity of the grains $\sqrt{gH_0}$ to the classical velocity of linear waves in shallow water $\sqrt{gh_0}$.



(a) (b) (c) (d)

Figure 1: (a) Sketch of the experimental setup, and pictures of the different wave shapes observed for different initial conditions : (b) nonlinear transition wave ($H_0 = 39$ cm, $L_0 = 5$ cm, $h_0 = 25$ cm), (c) solitary wave ($H_0 = 29$ cm, $L_0 = 10$ cm, $h_0 = 9$ cm), and (d) hydraulic jump ($H_0 = 39$ cm, $L_0 = 14.5$ cm, $h_0 = 3$ cm). The inset of each figure shows the initial state of the experiment.

RESULTS

The following parameters are systematically extracted from the movies of the experiments : the maximum wave amplitude A_m, the corresponding wave mid-height width λ_m, and the maximum horizontal velocity v_f of the granular front at the interface $z = h_0$. Doing so, it is possible to estimate a local Froude number $\mathrm{Fr}_f = v_f/\sqrt{gh_0}$, which compares the typical velocity of the collapse to the water wave velocity [4].

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For a given initial granular column, three distinct wave regimes are found when varying the initial water depth h_0, and thus the Froude numbers. For low values of the Froude numbers, a long primary wave followed by a weak dispersive wave train is observed (Fig. 1(b), for $\mathrm{Fr}_0 = 1.25$ and $\mathrm{Fr}_f = 0.19$), which corresponds to the nonlinear transition waves reported by [2] and [5]. At moderate Froude numbers, quasi-symmetrical solitary waves are observed (Fig. 1(c), for $\mathrm{Fr}_0 = 1.80$ and $\mathrm{Fr}_f = 0.52$), that can either break or not depending on the value of A_m/h_0 reached by the wave. Finally, for high Froude numbers, waves are close in shape to hydraulic jumps, breaking near the collapse region, due to the shock produced at the interface between grains and water (Fig. 1(d) for $\mathrm{Fr}_0 = 3.61$ and $\mathrm{Fr}_f = 1.86$).
Based on the local Froude number Fr_f, all data collapse onto a master curve for the relative wave amplitude A_m/h_0 [Fig. 2 (a)]. The first regime [I] observed for $\mathrm{Fr}_f \lesssim 0.35$, is very similar to the solution described by [6]. Waves are found to be highly unsteady, growing in amplitude until reaching a maximum, before flattening with a decreasing amplitude and a growing width. For $0.35 \lesssim \mathrm{Fr}_f \lesssim 0.87$ (regime [II]), waves are in good agreement with the Korteweg-de Vries theory (dash-dotted red curve in Fig. 2(a) and Fig. 2(b)), for both the amplitude and the mid-height width. Finally, for $\mathrm{Fr}_f \gtrsim 0.87$ (regime [III]), the hydraulic jump theory predicts well the maximum wave amplitude (solid black curve in Fig. 2(a)).

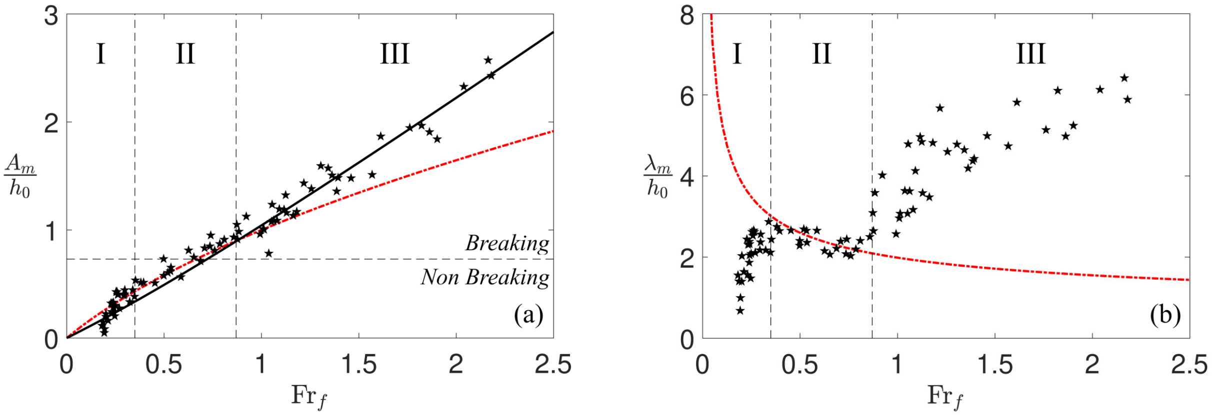

Figure 2: Evolution of (a) the relative amplitude A_m/h_0 and (b) the relative mid-height width λ_m/h_0 of the wave with the local Froude number Fr_f for all experiments (★); (—) : prediction from a hydraulic jump model; (-··) : predictions from Korteweg-de Vries solitary wave model; The horizontal dashed line corresponds to the breaking criterion $A_m/h_0 = 0.73$; The two vertical dashed lines correspond to the transitions at $\mathrm{Fr}_f = 0.35$ between nonlinear transition waves (I) and solitary waves (II), and $\mathrm{Fr}_f = 0.87$ between solitary waves (II) and hydraulic jumps (III).

CONCLUSIONS

In this study, tsunami waves generated by a granular collapse display different shapes governed by a local Froude number Fr_f based on the horizontal velocity of the granular collapse at the water surface. For $\mathrm{Fr}_f \lesssim 0.35$, nonlinear transition waves are generated, whereas for $0.35 \lesssim \mathrm{Fr}_f \lesssim 0.87$, solitary waves are observed and well described by Korteweg-de Vries theory. Finally, for $\mathrm{Fr}_f \gtrsim 0.87$, hydraulic jumps arise in response to the strong shock at the interface. These experiments allow to characterize the hydrodynamics of landslide generated waves, for a range of initial conditions that cover most of the real cases observed in Nature [7].

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