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PROPAGATION AND RUNUP OF TSUNAMIS GENERATED BY GRAVITATIONALLY ACCELERATED GRANULAR LANDSLIDES

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ABSTRACT

Landslide generated tsunamis are major hazards for developed areas on lakes and reservoirs, with wave transformations in shallow water and runup on slopes that can result in wave damage and flooding even at high elevations above the still water level. In this study we combine experimental observations and numerical predictions of near-solitary waves generated by granular landslides to investigate propagation out of the near-field generation region, runup, and reflection from a sloping boundary. Experiments are performed in a landslide flume consisting of an 8.2 m long 30° landslide slope to gravitationally accelerate granular landslides into a 2.1 m wide and 33.0 m long wave flume that terminates with a 27° runup slope, with a still water depth of 0.5 m in the reservoir. The SWASH model, a non-hydrostatic wave-flow numerical model, is applied to simulate the landslide-generated waves along the flume and interaction with a slope. The results show good agreement between the observations and predictions, indicating that the numerical model is an accurate tool for estimating the propagation and runup of nonlinear waves like landslide-generated tsunamis.

KEWORDS: landslide waves, tsunamis, numerical modelling, physical modelling, wave runup

1 INTRODUCTION

Landslide generated displacement waves, or landslide tsunamis, are waves created by the impact of a landslide into a body of water. These waves are major hazards for developed areas on lakes and reservoirs, since wave transformation in shallow water and runup on slopes can result in wave damage and flooding even at high elevations. Kamphuis and Bowering (1970) made the first attempt to relate the characteristics of landslide waves with slide parameters and receiving water properties, using experimental observations of a rock mass slide into in a wave flume. Recent experiments have used pneumatic acceleration of a granular slide mass (e.g. Fritz *et al*., 2004; Heller and Hager, 2010; Fuchs *et al*., 2013; Heller and Spinneken, 2013), however in this approach the landslide is relatively short and thick, with a porosity similar to the initial grain packing. In nature landslides and debris flows are driven by a longitudinal body force due to gravity that imparts a shear stress that increases with depth below the surface and influences the local granular pressure gradient and grain concentration (Iverson, 1997). In the present study we experimentally address the problem as defined is Figure 1, where a granular source volume is released down a slope and accelerates under the force of gravity forming a relatively long and thin landslide with velocity v_s that enters a reservoir. The impact of the granular mass, that has significant void space due to air entrained during the slide, generates a rapid change in the water surface elevation $\eta(x,t)$. The largest wave has a maximum amplitude $a_m(x)$ above the still water level h that propagates away from the source region at speed c where x,y are horizontal coordinates along and across the flume respectively, z is the vertical coordinate and t is time.

Different numerical models have been used to predict the generation and propagation of surface waves. These models require high temporal and spatial resolution to simulate rapid changes in wave shape due to dispersion and non-linearity. One type of model is non-hydrostatic phase-resolving models like SWASH (Zijlema *et al*., 2011) and NHWAVE (Ma *et al*., 2012) that are based on the conservation of momentum using the non-linear shallow water equations, extended to include non-hydrostatic pressure terms and vertical motions. SWASH, for example, has been used to simulate runup on slopes with results that compare well with measurements in a wave flume for cases of waves on a beach (Ruju *et al*, 2014). NHWAVE has been recently used to simulate granular slides (Ma *et al*., 2015) and compared with to experimental data from Heller and Hager

(2010) for pneumatically-accelerated slides down a short (3 m) slope. In this study we combine experimental observations gravitationally-accelerated landslides into large-scale flume with numerical predictions using SWASH to investigate wave propagation out of the near-field generation region, and runup and reflection from a sloping boundary.

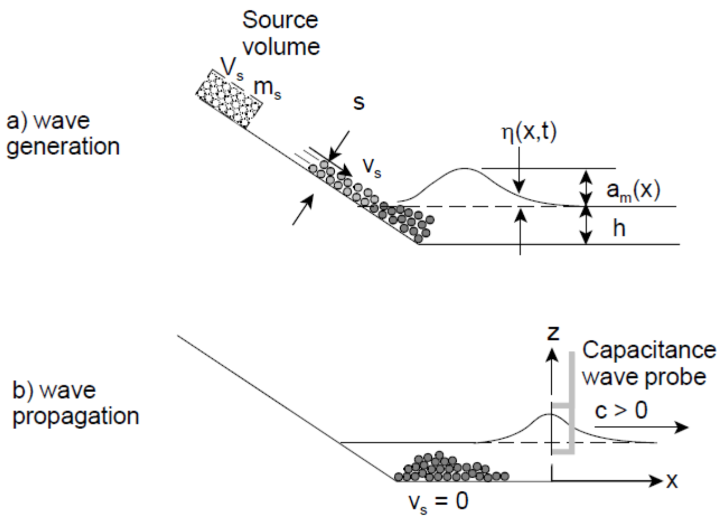

Figure 1. Physical modelling of landslide tsunamis: a) wave generation by gravitational acceleration of granular landslide mass into the flume; b) wave propagation away from the generation zone.

2 PHYSICAL MODEL OF LANDSLIDE WAVES

The Queen's University landslide flume consists of an 8.2 m long slope (6.7 m from the front edge of the source to the water surface), inclined at 30° to the horizontal which can be used to gravitationally accelerate granular landslides into a 33 m long horizontal wave flume at the base of the slope. The width and height of the flume are 2.09 m and 1.21 m respectively. The configuration of the flume illustrated in Figure 2, with the source volume release box at the crest of the landslide slope, the impact zone at the base of the slope, the wave propagation zone with capacitive wave probes installed at five locations along the flume to capture wave evolution, and a runup ramp located at the end of the flume.

The flume is capable of modelling granular landslides of volumes up to 1.68 m^3, and the volume tested in the present study is 0.34 m^3 arranged in a triangular source volume. Experiments in this laboratory facility are described in detail by Bryant *et al*. (2015) for landslides into a dry flume. The granular landslide material is 3 mm diameter spherical ceramic beads with a dry unit weight of 14.8 kN/m^3, specific gravity of 2.4, and a critical state friction angle of 33.7° (Raymond, 2002). The granular source volume is held in an aluminum release box with a pneumatically activated hinged door, that when triggered rapidly retracts and opens at a tip angular velocity of approximately 1 m/s as it rotates about the hinge at the top of the door. On release, the granular mass accelerates under gravity until it impacts the water reservoir in the flume.

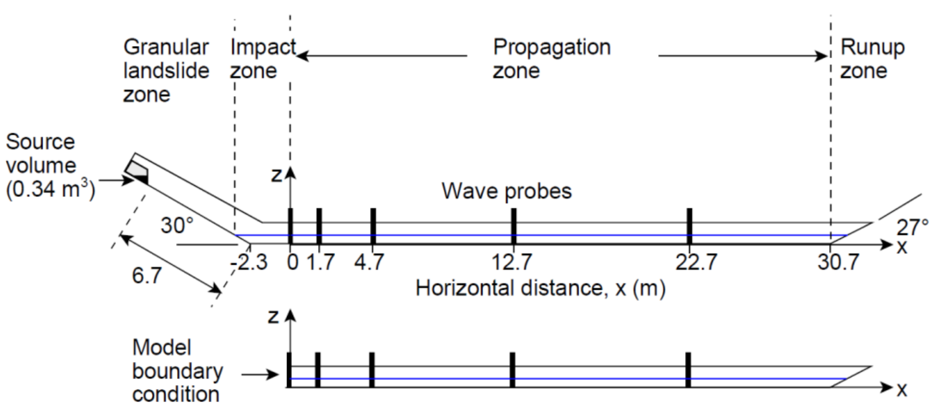

Figure 2. Experimental setup with the source, impact, wave propagation and runup zones for the physical model of landslide waves (top), and the numerical model with input boundary condition applied at x = 0 (bottom).

The landslide properties are measured at the toe of the slope using high-frequency digital images with a Phantom v9.0 high-speed camera operating at 1000 frames per second (fps). Images of the near-field wave generation zone are recorded using a Canon DSLR camera at 60 fps. Several images at selected at times (Figure 3) show the still water level before landslide impact, wave generation during landslide impact and wave propagation out of the near-field region after formation of the landslide deposit. These observations indicate that the gravity-driven granular slide creates a submarine density flow and a major surface wave, but does not form an impact crater or a region of surface splash as in previous experiments using pneumatically accelerated slides. The 20 Hz capacitance wave gauges are located at *x* = 0.0 m, 1.7 m, 4.7 m, 12.7 m, and 22.7 m, where the base of the landslide slope is located at *x* = -2.3 m. The distance from the corner of the landslide slope to the first wave probe was determined by the maximum runout distance of the granular material, such that the wave probe could measure accurately just beyond the submarine landslide. At the far end of the flume runup is measured using a GoPro Hero camera mounted to face the runup slope, which is labelled with elevation measurements relative to the vertical datum.

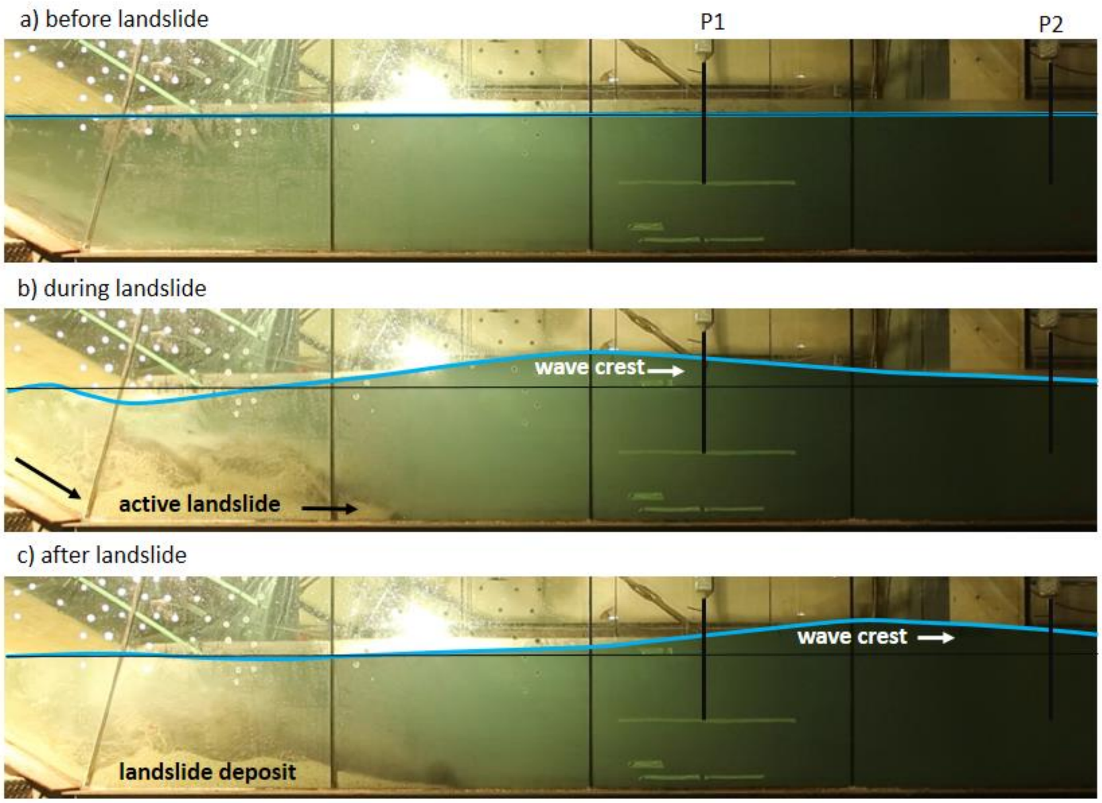

Figure 3. Instantaneous images from the 60 fps Canon DSLR camera indicating: a) the still water level before landslide impact; b) wave separation from the generation zone during landslide impact; c) wave propagation after landslide deposition.

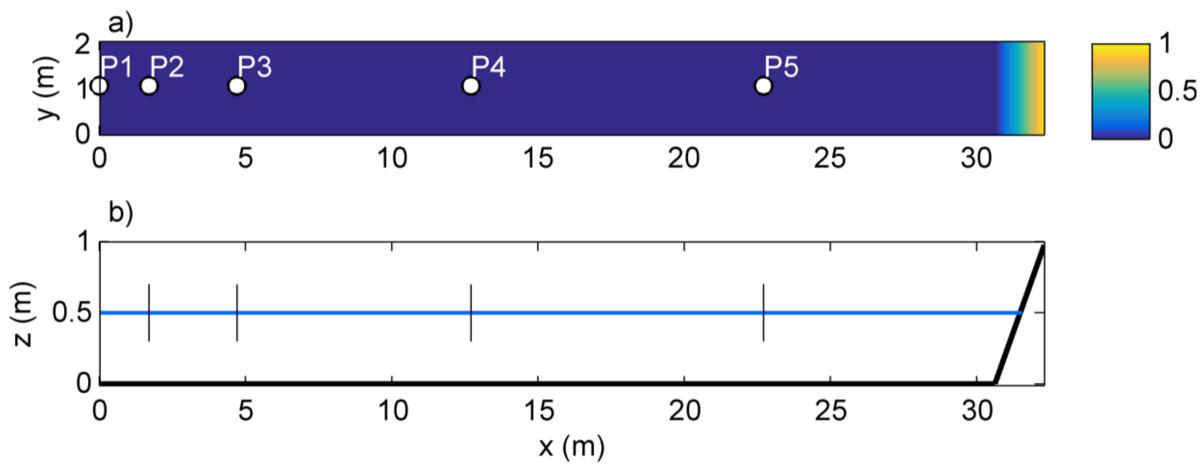

Figure 4. Numerical model domain: a) plan view with elevation contours (m) and wave probe locations P1-P5; b) side view indicating flume bottom at z = 0 m, still water level at z = 0.5 m, wave probes and runup slope at x > 30.7 m.

3 NUMERICAL WAVE MODEL

The numerical model is SWASH (Simulating WAves till SHore), a non-hydrostatic wave-flow model that uses a finite-difference approach to solving the fluid momentum and continuity equations (Zijlema *et al*., 2011). The 3D model was implemented on a uniform rectangular grid that extends from $x = 0.0$ m at wave probe P1 to $x = 33.0$ m at the end of the runup slope shown in Figure 4. Corresponding exactly to the flume, the bathymetry in the numerical grid is flat ($z = 0$ m) and slopes upward at 27° starting at $x = 30.7$ m. The still water depth is defined at $z = 0.5$ m, which intersects the runup ramp at $x = 31.4$ m. The horizontal resolution is 0.1 m and two layers are used to define the vertical grid. A water level boundary condition is imposed at $x = 0.0$ m, defined by time series observations from P1. At this location, an open boundary is also defined to allow waves to freely leave the computational domain and prevent reflection. This condition also allows the fluid velocity to adjust to the rapid changes caused by water levels at the input boundary. The model time step is 1×10^{-6} s and the model duration is 40 s, covering the time of landslide-generated wave travel along the flume, runup on the slope and propagation of the reflected wave back to the source region. Bottom friction is included using the Manning equation resulting in a spatially constant bottom friction coefficient of $c_f = 0.0060$. This value, which is higher than the model default value of 0.0019, was not estimated experimentally but was determined by model calibration and results in the highest agreement with wave observations. The bottom friction coefficient is the only model parameter that was varied to match the amplitude and arrival time of the wave at the probes.

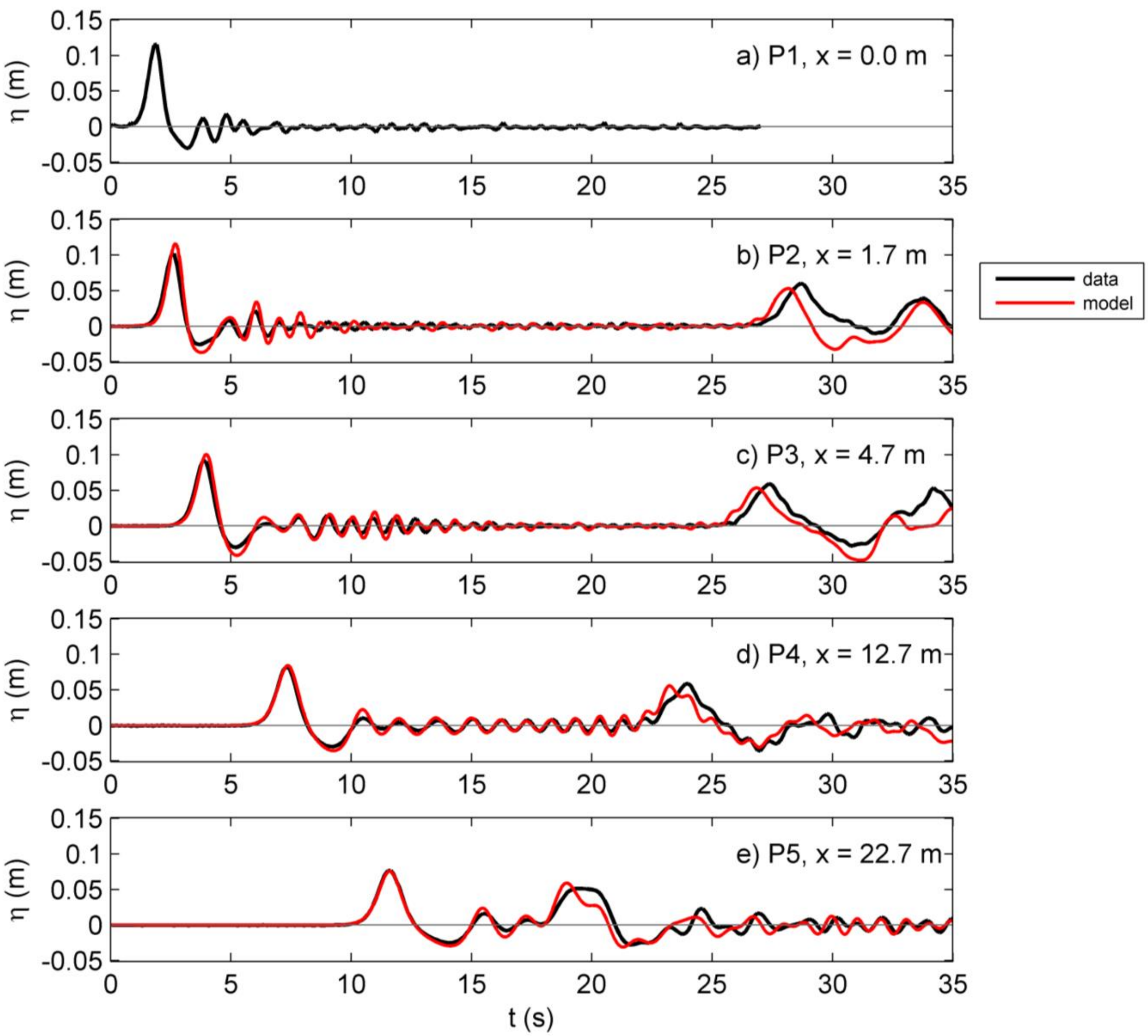

Figure 5. Observed and simulated water surface evolution with time at wave probe stations along the flume for incident waves and reflected waves.

4 RESULTS AND DISCUSSION

Wave observations at the probes are compared with model results at the same locations in Figure 5. The time-series indicate that the model is able to simulate the shape and timing of the leading largest wave, the train of smaller waves, and the reflected waves. The maximum amplitude of the largest wave a_m is shown in Figure 6. Both model results and observations in Figures 5-6 indicate a reduction in amplitude along the flume, governed by frictional dissipation of the shallow water wave. The model results do not exactly match the observations at P2 and P3, likely due to adjustment of the velocity field to the imposed water surface elevation change at the boundary (P1). Analysis of digital imagery suggests that submarine landslide flow generates a vertical velocity profile with strong near-bed flow in the near-field zone, and this is not simulated by the model. Future experiments will be used to quantify the velocity field and improve boundary conditions in the numerical model. However, the present model provides very accurate predictions of the water surface elevation in the far-field region, after adjustment to the rapid variations in the near-field zone.

When the waves encounter the ramp at the end of the flume, they runup the slope and reflect back. The reflected waves are evident in the time series in Figure 5 (*e.g.*, from t = 17 s at P5 to t = 28 s at P2) and there is good agreement in amplitude and phase between the experimental observations and model results. Predicted water level profiles at the runup slope are shown in Figure 7, and at the time of maximum runup the model results agree within 7% with the observed maximum water level elevation on the slope.

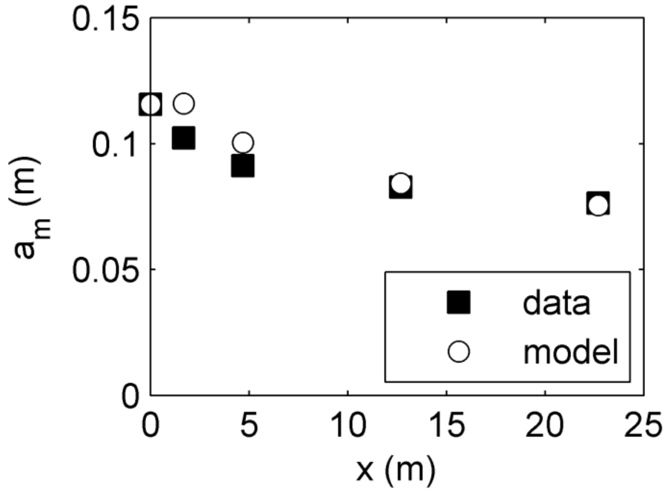

Figure 6. Observed and simulated maximum wave amplitudes at wave probe stations.

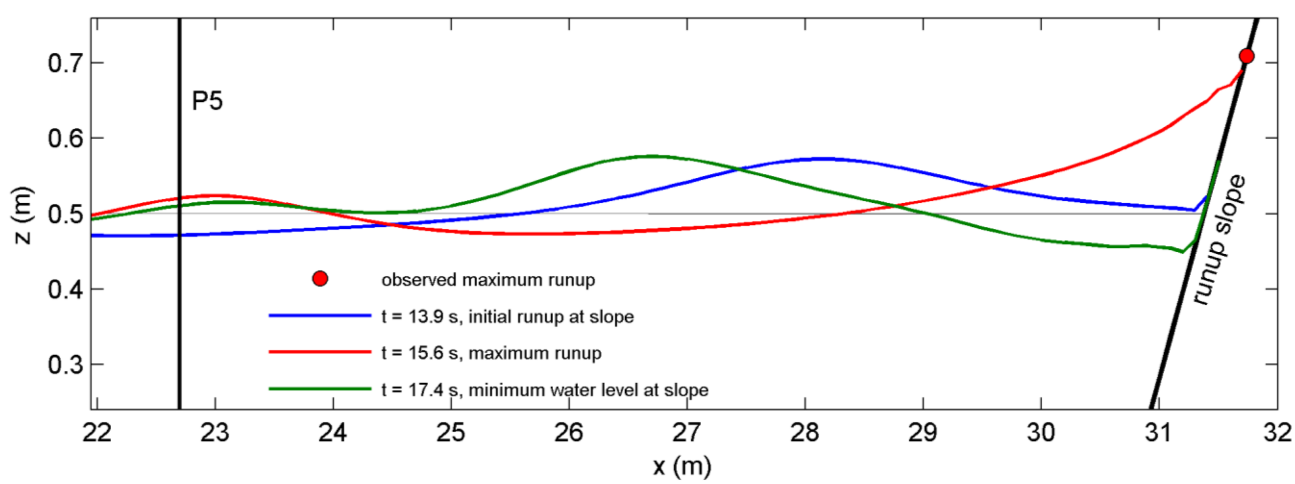

Figure 7. Model simulations of the water surface profile from wave probe P5 to the runup slope at selected times, and the location of the observed maximum runup elevation.

5 SUMMARY AND CONCLUSIONS

Observations from high speed digital cameras indicate that the gravity-driven granular slide experiment reported in this paper created a submarine density flow and a major leading surface wave, but did not form an impact crater or a high region of surface splash as in previous experiments using pneumatically accelerated slides. The present laboratory results indicate that compared to these previous studies with a much shorter wave flume (Fritz *et al*., 2004; Heller *et al*., 2010), these landslides generate tsunamis with a very different shape whose evolution can be captured as they propagate away from the near-field region at the landslide source to the far-field. The surface waves are numerically simulated using a non-hydrostatic model, and compared to wave probe measurements from a granular landslide in a flume with a 0.5 m deep reservoir. The results show good agreement between the observations and predictions, indicating that the numerical model is an accurate tool for simulating the propagation, frictional dissipation, runup and reflection of nonlinear waves such as landslide-generated tsunamis. These preliminary results indicate that further research is warranted to define the near-field waves generated by these slides for a wide range of slide parameters and reservoir levels, and to quantify the transformation of these waves from the near-field generation zone to the far-field region where runup is a major hazard on coasts. The fact that our first test showed results so different from previous work indicates that more large-scale experiments of gravity-driven slides are needed to better define the range of tsunamis generated by landslides.

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