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LANDSLIDE GENERATED TSUNAMIS: NEW LABORATORY EXPERIMENTS AND THEORETICAL DEVELOPMENTS

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Abstract: Landslide generated tsunamis are major hazards on mountainous coasts that can cause natural disasters due to vast inundation of coastal communities. To investigate the complex process of tsunami generation by landslides, experimental observations are obtained by releasing material and capturing the wave behavior with high speed digital cameras and wave probes in a large laboratory landslide flume. These detailed observations are used to validate a new expression that describes the wave amplitude in the near-field zone. The theoretical relationship that governs the maximum wave amplitude is derived by considering the transfer of momentum from the sliding mass to the water. This work provides a new method for predicting the landslide wave amplitude that is easily applied in practice. The results can be used in the near-field evaluation of tsunamis or to define boundary conditions for numerical models to determine the extent of wave propagation and run-up from these major coastal geo-hazards.

1 INTRODUCTION

Tsunamis have caused some of the worst natural disasters in the world, with energetic waves that can inundate vast areas of land with hazardous debris-laden flows. Recent events have resulted in high loss of human life and high costs to rebuild infrastructure such as the earthquake-generated tsunami in Japan in 2011 that resulted in over 15,000 casualties and cost over $200B (Mimura et al. 2011). Tsunamis triggered by landslides in mountainous regions have immense local impacts with run-up over 100 m above shorelines. Recent examples include the massive slide into Icy Bay Alaska that resulted in run-up over 190 m in 2015 (Lynett et al. 2016), and the rapid rock avalanche into Karrat Fjord in Greenland with 45 Mm^3 of material entered the fjord along less than 1 km of shoreline over a period of only 2–3 min (Gauthier et al. 2018). In the latter case, the huge wave wiped out the small coastal community of Nuugaatsiaq.

To predict the waves generated by landslides, laboratory experiments can be carefully performed to make detailed measurements (e.g., Heller and Hager 2010; Miller et al. 2017; Bullard 2018), and the data used to develop empirical formulae that describe the wave characteristics from fitting parametric expressions to the observed data (e.g., Heller and Hager 2010). Alternatively, the data can be used to validate analytical solutions. For example, Mulligan and Take (2017) considered the momentum flux from a landslide to a water body, and derived idealized theoretical relationships for the maximum wave amplitude in the near-field zone. The problem is depicted in Figure 1, where the tsunami generation process necessitates understanding of the landslide, impact with water, momentum transfer, and near-field wave transformation due to wave breaking.

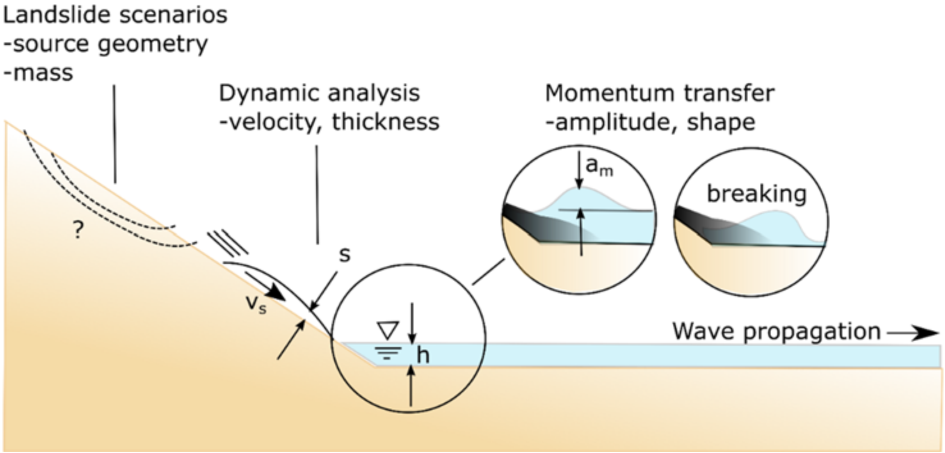

Figure 1: Conceptual diagram of the landside tsunami generation process: landslide, impact with water, momentum transfer, wave transformation and propagation.

In the present paper we describe the results of new laboratory experiments performed by Bullard (2018) in Section 2, discuss results from a predictive equation developed by Mulligan and Take (2017) in Section 3, and provide conclusions in Section 4 on the generation of tsunamis from landslides.

2 EXPERIMENTAL OBSERVATIONS

Laboratory experiments are performed in a landslide flume consisting of an 8.23 m long slope inclined at α = 30° to the horizontal to gravitationally accelerate landslides into a 33.0 m long and 2.1 m wide horizontal wave flume described in detail by Miller et al. (2017). Material is released from a source volume box at the top of the slope, accelerates down the landslide slope and impacts the water where it generates waves. The waves transform and propagate along the flume, run-up the slope at the end of the flume, and reflect back.

In the present study we examine a sub-set of the data collected by Bullard (2018). In these experiments, a triangular source volume V of water (ρ_s = 1000 kg/m^3) is used to generate a highly mobile slide with high impact velocity. The landslide and near field wave properties are observed using a system of high-speed cameras. The water surface is also measured using nine capacitive probes (P1-P9) along the flume at x = [2, 3, 6, 9, 11, 17, 21, 25, 33 m] that sample at 100 Hz. The water depth h is varied from 0.15-0.65 m and in total 41 tests are conducted, with a sub-set of preliminary data from 11 tests presented here.

The range of source volumes tested include V = [0.1, 0.2, 0.3, 0.4 m^3], which results in a range of landslide velocities v_s = 5.08-6.51 m/s and slide thicknesses s = 0.02-0.06 m at impact with the reservoir. The submarine part of the slide has effective length L_e= 0.8-2.4 m and effective time Δt_e= 0.44-0.83 s from the point of impact until the wave speed exceeds the decelerating slide speed and the wave detaches. An example of wave generation from the point of impact to wave detachment from the submarine part of the slide is shown in Figure 2 for the case with V = 0.3 m^3 and h = 0.30 m. The corresponding time series of water level elevations measurements at the wave probes are shown in Figure 3.

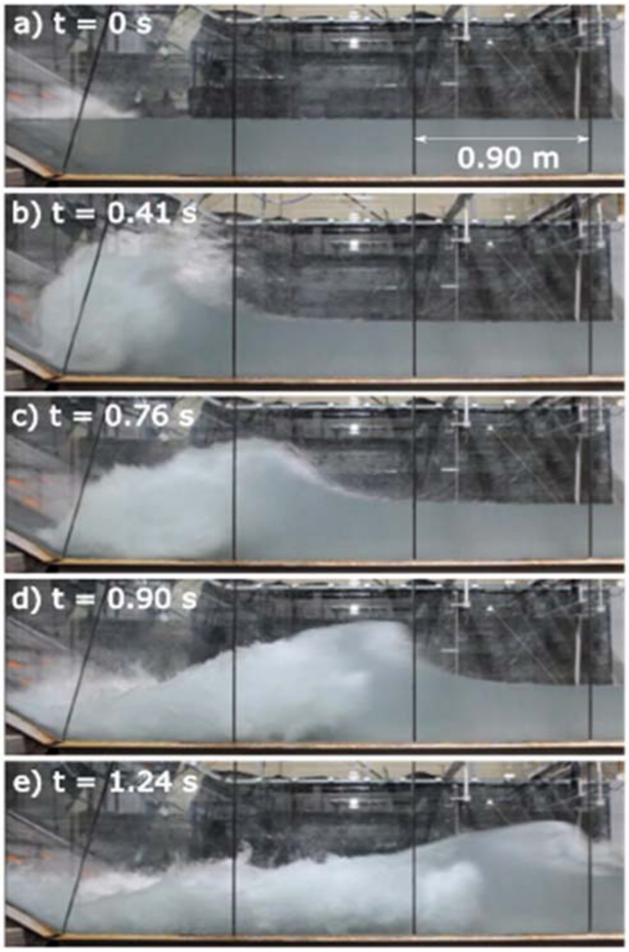

Figure 2: Near-field image time series of landslide wave generation in the laboratory.

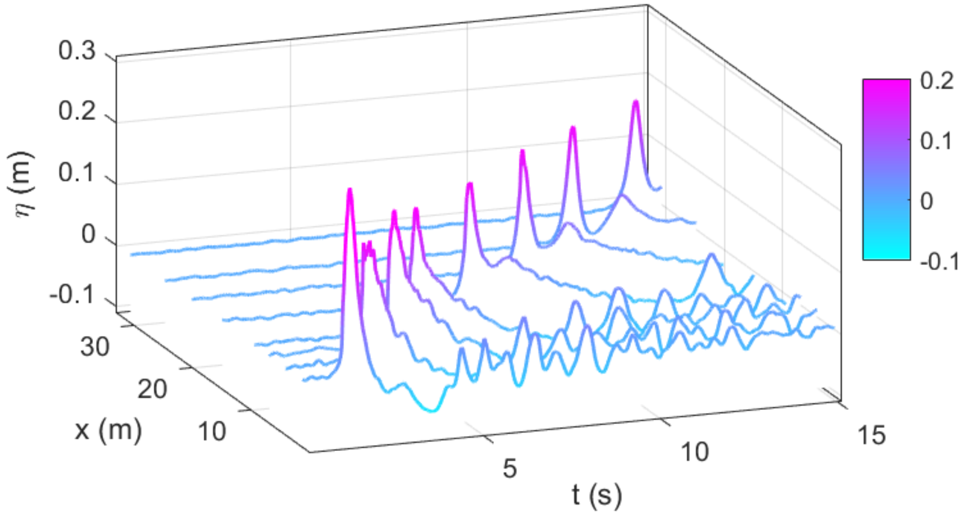

Figure 3: Time series of water level (η) observations at wave probes P1-P8 during landslide wave transformation and propagation.

3 THEORETICAL CONSIDERATIONS

Mulligan and Take (2017) consider a 1-dimensional approach to analyze the state of the bulk fluid at landslide impact. In this scenario, momentum that is transferred to the water is expressed by the hydrostatic pressure gradient generated by a near-instantaneous vertical water level displacement over a short time scale Δt_e and length scale L_e. The initial pressure gradient is evaluated from the change in water surface elevation $\eta(x,t)$, that has a maximum positive wave amplitude a_m above the still water depth h between two points in the landslide impact zone and the zone unaffected by the slide. The analysis yields the equation:

$$[1] \qquad a_q = \sqrt{h^2 + \frac{2\rho_s s v_s cos\alpha L_e}{\rho g \Delta t_e}} - h$$

where a_q denotes the maximum near-field wave amplitude derived from a quadratic equation, ρ is the fluid density and g is gravitational acceleration.

The observations and predictions of relative wave amplitude (a_m/h) are shown at several locations along the flume in Figure 4, where perfect agreement with Eq. [1] results in points along the 1:1 line. At the near-field wave probe (P1 at x =2 m) the agreement is good but not perfect, however at the far field sensors (e.g., P7 at x =22 m) the maximum wave amplitude is very well predicted for non-breaking waves with low values of a_m/h. This is due to depth-limited wave breaking, an important consideration for these highly turbulent flows, which causes an immediate reduction in amplitude as a function of h. The effect of breaking is indicated by the change in relative amplitude from near-field to far-field sensors. The overall agreement between data and model results suggests that the range of validity for the theoretical equations developed for granular landslides can be extended to slides with higher mobility. The predictive framework can therefore be a useful method of defining the boundary conditions for numerical models used to simulate the water surface (e.g., Mulligan et al. 2016) and flow velocity (e.g., Mulligan et al. 2018) evolution of landslide tsunamis.

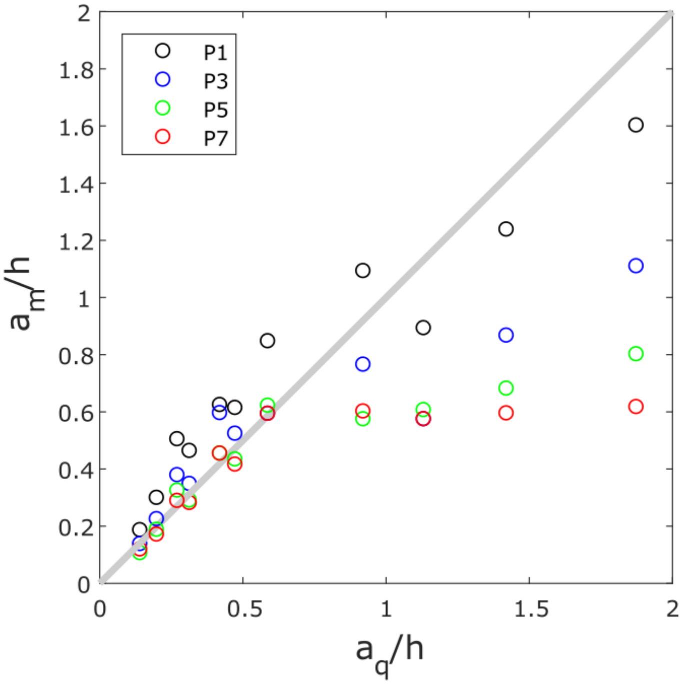

Figure 4: Comparison of observations (circles) for sub-set of tests from Bullard (2018) with the theoretical relationship for momentum balance from Eq. [1] at selected wave probes.

4 SUMMARY AND CONCLUSIONS

New insight into the generation of waves by landslides is acquired by conducting experiments in a large scale flume and developing a momentum-based predictive framework. In this paper, we extend the range of validity for a theoretical equation developed for granular landslides (Mulligan and Take 2017) to slides with higher mobility based on preliminary data from new experiments (Bullard 2018). The predictions of maximum wave amplitude are validated by tests for the highly mobile slides, and the results are in good agreement with observations except where the amplitude is reduced due to depth-limited wave breaking. The overall agreement suggests that the range of validity for the momentum-based equation developed for granular landslides can be extended to slides with higher mobility.

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