Parametric study of landslide generated impulse wave physical modeling

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ABSTRACT
Landslide generated impulse waves, or landslide tsunamis, are waves created by the impact of landslides into a body of water. In smaller bodies of water, such as lakes or fjords, the impact site can be very near developed areas, and the impulse wave can pose a significant risk. In dam reservoirs, impulse waves can create a risk of overtopping. Current studies in this field have focused on small and thick landslides which behave like a solid block. However, many landslides which may govern risk assessments tend to flow and spread out, resulting in a long and thin time-varying flow of granular material, despite their large mass. This paper describes the development of a physical model of landslide generated waves. Preliminary numerical model results of a granular landslide analyses are presented to demonstrate the range of landslide parameters in the context of previous studies.

RÉSUMÉ
Les ondes de translation, ou les tsunamis générés par les glissements de terrain, sont des vagues crées par l'impact du glissement de terrain dans un plan d'eau. Dans les petits plans d'eau comme les lacs ou les fjords, le site d'impact peut se trouver très près de zones développées et les vagues ainsi générées peuvent être un véritable risque. Dans le réservoir des barrages, les ondes de translation peuvent créer un risque de débordement. Les études actuelles dans ce champ de recherche se sont focalisées sur de petits glissements de terrain épais, se comportant comme des blocs solides. Cependant, un certain nombre d'autres glissements de terrain à risque ont tendance, en dépit de leurs masses, à s'écouler et à s'étendre, formant ainsi un flux de matériaux granulaires longs et fins, évoluant avec le temps. La présente étude décrit le développement d'un modèle physique axé sur les vagues générées par les glissements de terrain. Les résultats préliminaires du modèle numérique basé sur les analyses granulaires d'un glissement de terrain sont présentés de manière à démontrer la gamme de paramètres liés aux glissements de terrain dans le contexte des études précédentes.

1 INTRODUCTION

Tsunamis are water waves typically generated by sea floor movements caused by seismic activity. Subaerial landslides into water can generate similar waves, although they may be smaller than seismic tsunamis. In smaller water bodies, such as lakes, fjords or dam reservoirs, these smaller waves can still be very damaging to structures along the shoreline. The most well-known example is the Vajont Dam disaster in Italy. In 1963 a 270 million m^3 landslide generated a 70m wave that overtopped the dam, and destroyed the town of Longarone (Genevois and Ghirotti 2005).

Extensive empirical experiments have been done at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) (Heller, 2008; Heller and Hagar, 2010; Heller and Spinneken, 2013; Fritz, 2002; Fritz, 2004) on granular landslide masses entering an 11m long 2-D wave flume. Empirical equations relating the landslide parameters (volume, thickness, velocity) to the wave properties (Heller 2008) and the wave types (Fritz et al, 2004) have been found. A pneumatic landslide generator was used to create landslide masses of varying dimensions by accelerating granular material into the flume at varying impact angles.

Previous work done in this field has focused on slides with small relative mass, but larger relative thickness. These landslides act as a block, instead of flowing down the test slope. However, many very large landslides do not slide like a block. Instead, they tend to break up and flow due to their rapid velocity and large size. Landslides of this nature are more likely to cause damage, and are therefore more likely to drive risk assessments.

This paper describes the laboratory facilities at Queen's University and presents preliminary results. Empirical tests are done with gravity-driven granular landslide material, travelling down an 8 m long slope inclined at an angle of 30°. The waves propagate along a 36 m wave flume and are measured with capacitance wave gauges. The landslide material consists of spherical ceramic beads (Denstone Ceramic Bed Support Media) with a diameter of 3mm. Figure 1 shows the landslide flume geometry.

In Section 2 we examine the geometry of landslides used in empirical tests of landslide generated waves. In Section 3 we give case histories of landslides demonstrating that fast moving, large volume landslides (which are of primary concern for wave related cases due to their likelihood of creating damaging waves) are more likely to flow than to move as a block. Section 4 describes the preliminary experimental results and numerical model test results that show the capabilities for future tests.

2 PHYSICAL MODELING OF LANDSLIDE-INDUCED IMPULSE WAVES

Empirical tests of landslide generated waves typically use two general material types to model the landslide mass: solid blocks or a mass of granular material. A comparison of landslide parameters tested in the literature and four case histories is shown in Figures 2, 3 and 4. Four dimensionless landslide parameters are discussed in this paper. The relative mass, M, relates the mass of the landslide to the mass of the displaced water. The relative thickness, S, relates the thickness of the slide to the depth of water. The Froude number, *F*, is the ratio of the slide velocity to the gravitational wave velocity. The impulse product parameter, *P*, relates all the governing parameters. It was used to optimize the data analysis of impulse wave generation (Heller and Hager, 2010). These dimensionless parameters are defined by Equations 1 – 4.

$$M = m_s/(\rho_w B h^2)\text{; Relative mass} \quad [1]$$

$$S = s/h\text{; Relative thickness} \quad [2]$$

$$F = v_s/(gh)^{0.5}\text{; Slide Froude number} \quad [3]$$

$$P = FS^{0.5}M^{0.25}\{\cos[(6/7)\alpha]\}^{0.5}\text{;} \quad [4]$$
Impulse product parameter

Where h is the water depth at impact, g is acceleration due to gravity, s is the landslide thickness at impact, ρ_w is the density of water, v_s is the landslide velocity at impact, B is the landslide width at impact, m_s is the landslide mass.

2.1 Tests using solid blocks

Panizzo et al. (2005a) performed a study using a solid landslide mass on a trolley sliding into a 3D wave basin. The wave basin was 12.0m long, 6.0m wide, and 0.8m deep. The landslide mass impacted the wave basin at one edge to take advantage of the symmetry of the generated wave. The largest relative mass, *M* and relative slide thickness, *S* tested in this research is 1.54 and 0.45, respectively. The slides modeled in this study were not very massive compared to the displaced water. The tested slides had maximum lengths of 0.415m and thickness of 0.18m and can be considered as blocky landslide geometry.

Heller and Spinneken (2013) performed tests in a flume 24.5m long, 0.6m wide and 1.0m high. They used solid landslide masses with a maximum relative landslide mass, *M*, of 1.21, maximum relative thickness, *S*, of 0.4. These tested landslides were slightly longer, maximum length of 0.64m and thickness 0.12m.

Sælevik et al. (2009) modeled tsunamis in a 2D flume measuring 25m long, 0.51m wide, and 1m deep. The slide mass was constructed from a series of solid blocks sliding on a trolley. Three different landslide lengths were tested: 1m, 1.6 and 2m. The blocks were 0.16m or 0.12m thick. These tests featured a long and thin landslide masses, however, the water depth in these tests was kept constant at 0.6m for all tests. The maximum relative thickness, *S,* and mass, *M,* was 0.27 and 0.81 respectively. The modeled slides were not large or thick compared to the displaced water depth.

Their work also indicates that “experiments with granular slide material are not directly transferable to experiments with non-granular slide material” (Sælevik et al. 2009).

2.2 Previous tests using granular material

The VAW experimental set up features a 2D flume, 11.0m long, 0.5m wide and 1.0m deep (Fuchs et al. 2013). The landslide is formed with a pneumatically operated generator, with a variable slide impact angle. The end of the flume is equipped with wave absorbers; run-up is not calculated. Fuchs et al. (2013) performed 300 tests with a maximum volume Vs, of $0.0668m^3$. Fritz (2002), Zweifel et al. (2006), Heller et al. (2008, 2010, 2013) all used the same testing facilities. Their parameter ranges are defined in Table 1.

Fritz et al (2004) also studied the wave types created by the range of landslide types as the waves propagated along the 11m long flume. This study found that wave types generated depended on *F* and S. The wave types were: nonlinear oscillatory waves; nonlinear transition waves; solitary-like waves; and dissipative transient bore.

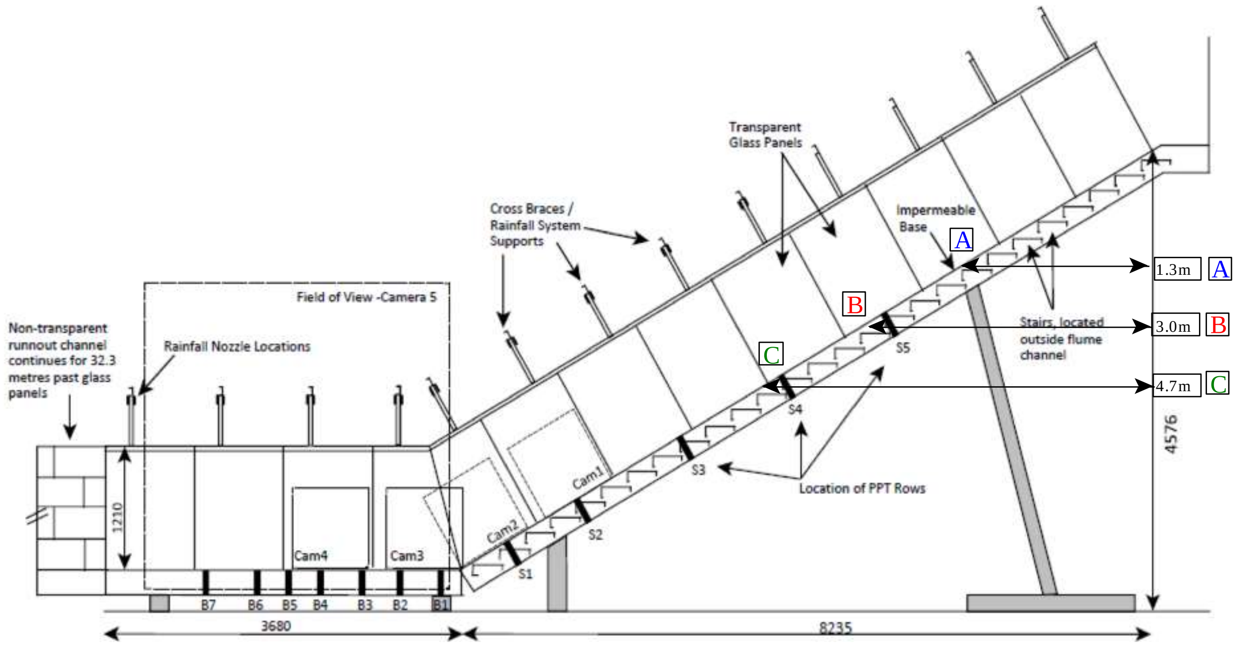

Figure 1: Landslide flume geometry, showing initial positions for Cases A, B, C

Table 1. Range of parameters tested in previous studies

Parameter		Fuchs	Zweifel	Heller	Fritz	Panizzo	Mohammed
S	MIN	0.076	0.08	0.09	0.076	0.1125	0.1
	MAX	1.639	1.13	1.64	0.663	0.45	0.9
M	MIN	0.11	0.11	0.11	0.119	0.0484	0.44
	MAX	10.019	3.588	10.02	2.403	1.54	52.8
F	MIN	0.86	1.08	0.86	1.25	0.999	1
	MAX	6.827	4.89	6.83	4.89	2.221	4

3 LANDSLIDE DIMENSIONLESS PARAMETERS IN FIELD CASES

It can be difficult to estimate landslide parameters from historical field cases. The exact conditions of the landslide as it occurs are rarely observed. Instead they are extrapolated from run out distances, initial conditions and site geology. In particular, *F*, which depends on the landslide velocity, can be very difficult to determine. The parameters *M* and *S* are easier to determine because the source volume and approximate thickness at impact are easier to estimate from geological data than the velocity.

Geist et al. (2003) and Wieczorek et al (2003) describe the preliminary assessment of the Tidal Bay Inlet landslide in Glacier Bay National Park, Alaska. This predicted landslide is estimated to have a length of 500m, thickness of 30m, and a total volume of $10x10^6m^3$. The water depth in this area is 200m. This landslide is less blocky than in previous studies, but has a relative mass of approximately 2, which is within tested ranges.

The Vajont Dam landslide of 1963 was very massive and fast moving. The estimated volume was $270x10^6m^3$ into a water depth of 236m (Genevois and Ghirotti, 2005). Therefore the relative mass is approximately 35, which is beyond the range tested in all but one study.

In the 1959 landslide event in the Pontesei reservoir, Italy, approximately $5x10^6m^3$ of material impacted the reservoir (Panizzo et al, 2005b). The reservoir water depth at the impact site was 47m. The relative mass of this landslide was approximately 82, well beyond the values tested previously.

In 2003, a landslide impacted the Three Gorges Reservoir, China. The $20x10^6m^3$ landslide impacted the 70m deep reservoir (Wang et al. 2004). The resultant relative mass of this landslide was approximately 99. Figure 2 shows the dimensionless parameters of these field cases as they compare to the tests done to date these are a few examples of the types of slides for which there is currently insufficient modeling. There is a clear need for more testing of landslides with very large relative mass.

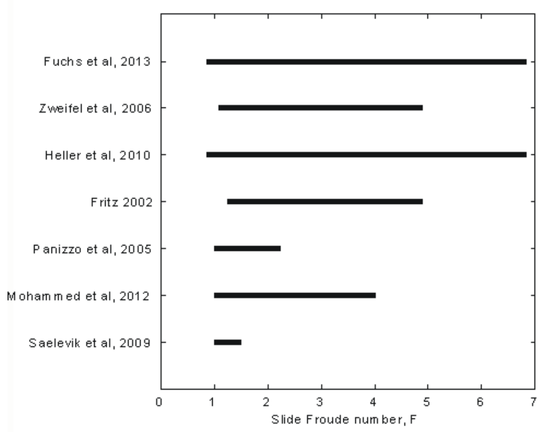

Figure 2. Comparison of slide Froude number tested in previous studies.

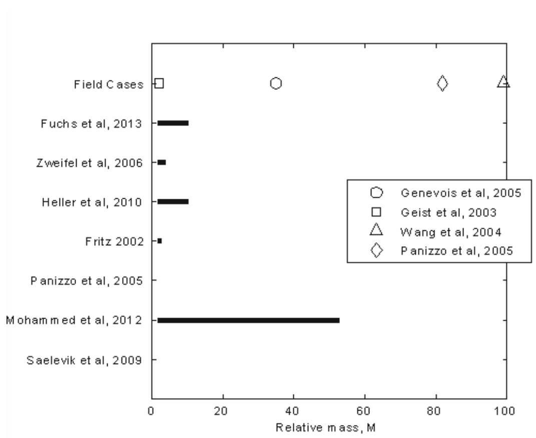

Figure 3. Comparison of relative mass, *M*, tested in previous studies and in field cases.

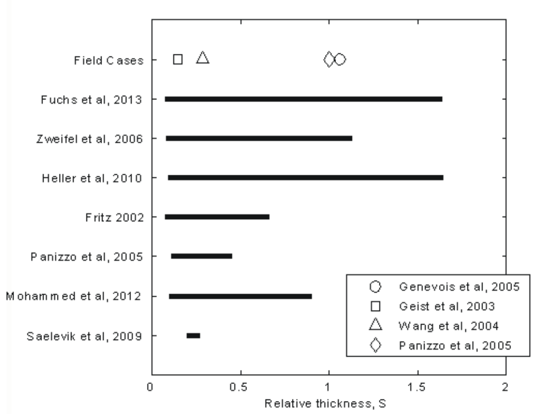

Figure 4. Comparison of relative thickness, *S*, tested in previous studies and in field cases.

4 QUEEN'S UNIVERSITY LANDSLIDE FLUME

The landslide flume at Queen's University is a 2.09m wide channel with an 8.23m long, 30º sloped section, and 36m long run out. The side walls are 1.21m tall, and in the first 3.68m of the run out section are made of 19mm tempered glass. The base of the flume is aluminum.

This flume is capable of modeling gravity-driven, dry granular landslides of volumes up to 1.68m^3. The material is held in a release box with a hinged door at the top of the sloped section. The release box has a hinged door which is controlled by a pneumatic air system and actuators (Bryant, 2013). In this study, the behaviour of the granular material was studied using Particle Image Velocimetry (PIV), characterizing the different phases of landslide movement.

The facility has been used to model dry granular landslides to determine the grain scale interactions and run out characteristics as they depend on basal friction and landslide volume (Bryant, 2013). It was also used demonstrate the impact that suction has in small-scale models of transient seepage triggered landslides. This study provided a direct comparison between small-scale centrifuge tests and reduced scale flume tests using nominally identical soils (Beddoe, 2014).

The geometry and set up of this landslide flume makes it ideally suited for modeling large landslides. Due to the large width and lack of a pneumatic device for accelerating landslide materials, very large masses (and therefore large relative mass, *M*) spread out and flow while they accelerate.

5 NUMERICAL MODELING OF FLUME PERFORMANCE ENVELOPE

Dan-W is a numerical model for simulating the flow of landslides, debris flows and avalanches. It is used to model a number of different flow rheologies and geometries in order to estimate flow velocities, thicknesses and runout (Hungr, 1995). It is used here to perform a parametric study of the landslide flume at Queen's University.

5.1 Dan-W Model Validation

Previous comparisons between Dan-W analyses and landslides modeled in this flume have shown close agreement between the two methods (Bryant, 2013). Figure 5 shows Dan-W results for 0.34m^3 compared to physical tests in the flume.

A Dan-W model of the testing facility allows for estimates of the range of parameters that can be achieved. The assumed material properties used in the model are as follows: unit weight, 20kN/m3; basal friction angle 25.5°; friction coefficient, 0.38; internal friction angle, 33.7°. The material is modeled as a purely frictional material.

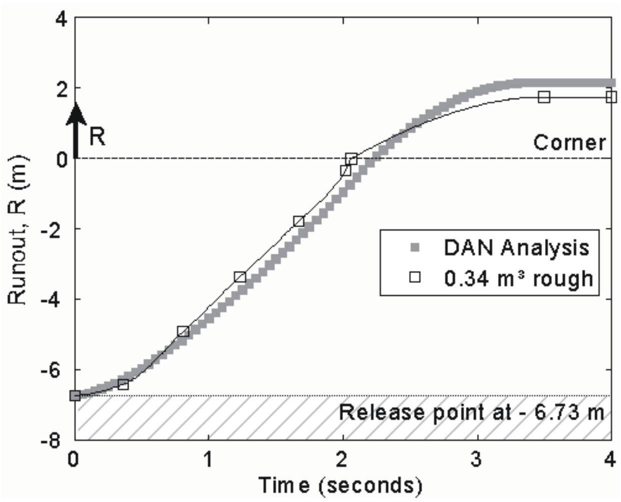

Figure 5. a) Runout distance with time for a 0.34 m^2 granular slide, where zero runout represents the transition between sloped and flat sections. From (Bryant, 2013).

5.2 Parametric Study

Estimating the landslide thickness and velocity that is most relevant for wave generation can be difficult. Granular landslides have been shown to exhibit different regimes of flow (Bryant, 2013), where each regime varies in thickness and velocity. In the Dan-W analysis, the representative landslide velocity (v) and thickness (s) was assumed to occur at the time step when the momentum term, v*s, was maximum. These terms were measured at the corner of the flume, the junction between the ramp and the run out zone. Nine different scenarios were tested in order to estimate the capabilities of the facility. Three different landslide volumes were tested, each at three different initial positions. Figure 6 shows the velocity and thickness values calculated in Dan-W for the three different volumes and three different landslide initial positions. Estimated landslide thickness is in the range of 0.03m – 0.16m, and the estimated landslide velocity is in the range of 2.03m/s – 3.19m/s. This study looks at water depths ranging from 0.1m to 1.0m.

Landslide parameters predicted in this study are compared in Figure 7 to the values from the previous studies and to case histories. The landslide flume used in the present study is capable of generating slides with larger relative mass, and therefore more representative of real landslides as compared with the case histories.

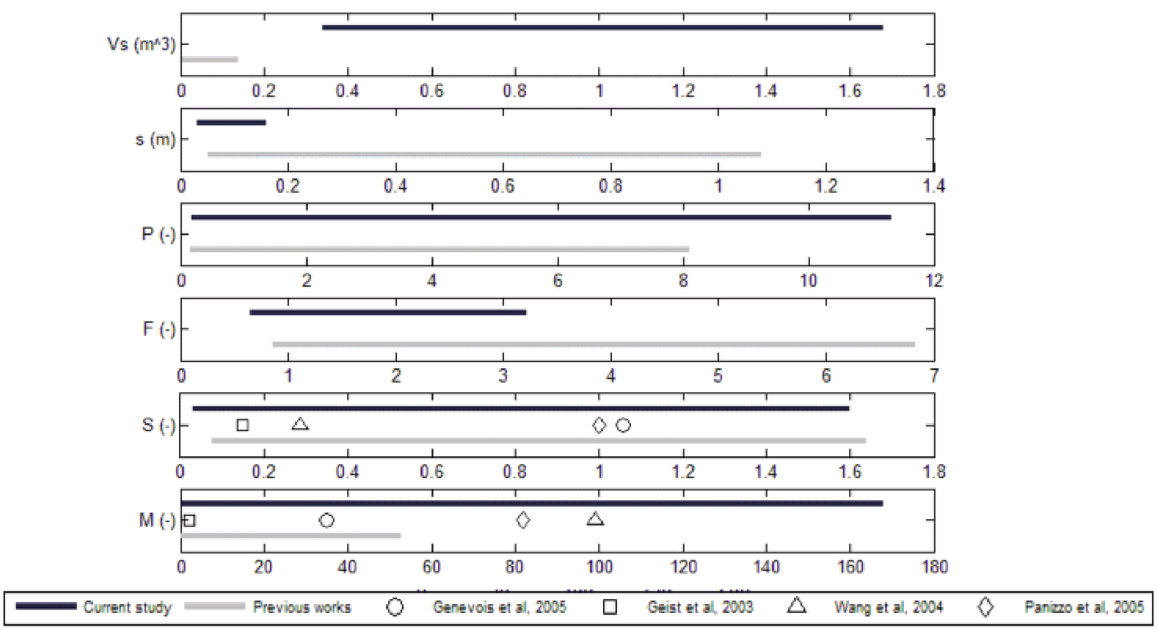

Figure 6. Comparison of landslide parameters tested in previous studies and the possible range estimated in this work.

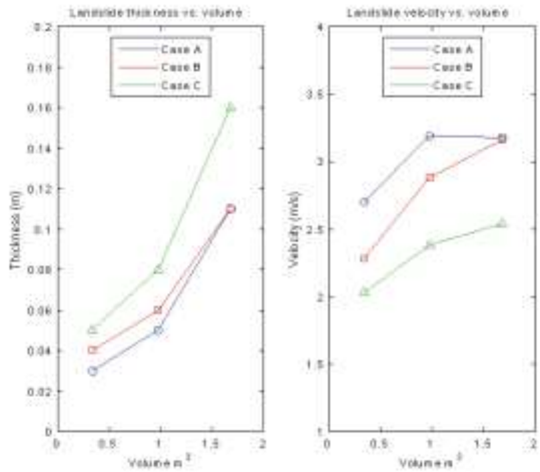

Figure 7. a) Thickness vs. volume and b) velocity vs. volume. Cases refer to initial position of landslide. Case A = 1.3m from start of flume; Case B = 3.0m from start of flume; Case C = 4.7m from start of flume. See Figure 1 for the initial positions of each case.

6 CONCLUSIONS

Wave generation by landslide impact has been previously studied for short, thick landslides, using both solid blocks and granular material. The landslide mass is typically accelerated pneumatically. A good reason for studying this geometry and with this type of facility is convenience; it is possible to get a wider range of landslide parameters without drastic changes to the volume or the testing apparatus.

However, many real world landslides, particularly very large and rapid landslides tend to flow and spread out over long distances. Large, rapid landslides are likely to govern landslide risk assessments, as they are more likely to cause significant damage. These landslides are therefore more likely to be the design landslide for the assessment for landslide generated waves. Understanding the generation of waves by large, rapid landslides which do not behave as a coherent block is important in this context.

The facilities presented here are capable of modeling landslides that are large, long and thin time varying flows of granular material. The granular material accelerated in the flume under gravity alone can more closely approximate very large, rapid landslide behaviour. The 36m long run out zone allows for a longer period of time to measure the wave forms created by these long landslides. Future tests will be performed for a range of water depths to determine the resulting wave properties for a wide range of relative landslide dimensions. Particle Image Velocimetry (PIV) will be used to measure velocity fields of the granular landslide mass and tsunami.

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