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Spatial and Temporal Evolution of Landslide-Generated Waves

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Abstract

The waves generated by an underwater landslide exhibit strong dependence on the landslide motion. In this experimental study, the landslide is modelled as a solid semi-elliptical block moving along a horizontal boundary in a flume. The landslide initially accelerated at a constant rate to its terminal velocity, and after travelling for 2 seconds at this velocity it decelerated to rest (at the same rate as its acceleration). An application of laser-induced fluorescence provided free surface elevation measurements along the flume length, generating a robust dataset to investigate the spatial and temporal evolution of the generated waves.

The landslide acceleration and Froude number (Fr) were varied during the experiments. The wave field is dominated by the acceleration-generated waves at low Fr, but at higher Fr energy is transferred from the landslide to the trailing waves during its constant-velocity motion. The landslide Froude number is the primary parameter affecting the evolution of the wave field, the magnitude of the landslide acceleration modifies the nonlinearity of the generated waves.

Introduction

Landslide-generated tsunamis are a hazard of significant concern to coastal communities, due to their relatively large waves (in the vicinity of the source) and the short time between wave initiation and impact. Resilience to landslide-generated tsunamis relies on data obtained from field investigations, predictive mathematical models and physical experiments. Mathematical models are often validated using the measurements obtained from physical experiments, which contain the full physics of wave propagation from an appropriate (often idealised) source mechanism. When the source mechanism is a submarine landslide, the possibility of ongoing interaction between the generated waves and the moving landslide creates an interesting fluid mechanics problem (albeit one with serious consequences in the field).

Previous physical modelling of wave generation by a submarine landslide has typically approximated the landslide as a solid block moving along a sloping surface under the influence of gravity within a long wave flume [3, 6, 2]. At laboratory scales, sensible solid-block landslide motion requires slopes that are often steeper than those encountered in the field. Granular landslides require additional forcing from a pneumatic piston or similar [1], applicable for subaerial generation only. For a thorough discussion of scale effects in the context of landslide-generated tsunamis, the reader is referred to Heller et al. [4]. A consequence of the gravity control of submarine block landslides is that the landslide motion may only be varied by changing the landslide mass or the slope angle (the latter typically limited by the experimental flume length). This necessarily limits the range of motion able to be tested.

Most previous experimental studies into landslide-generated tsunamis used wave gauges to obtain free surface elevation time series at discrete locations. Some have also used flow visualisation methods such as particle image velocimetry (PIV) or particle tracking velocimetry (PTV) to measure the fluid velocities in the vicinity of the moving landslide [1, 5]. Data measurement at discrete locations is more practical in most laboratory facilities. However, the dispersive nature of landslide-generated waves means that such discrete measurements may not capture the key features of the wave field (or even the maximum amplitudes of the generated waves). Additionally, mathematical models are becoming more sophisticated and quicker/cheaper to run. With such models providing predictions of free surface elevation and fluid velocity over a large spatial and temporal domain, the validation data required should include adequate resolution in both space and time.

This paper describes a series of experiments investigating the waves generated by the motion of a solid block over a horizontal boundary within a (1DH) wave flume. A computer-controlled servo motor provided highly repeatable landslide motion, with the ability to vary the motion of the landslide over a broad parameter space. Free surface elevations were provided by an application of the laser-induced fluorescence (LIF) technique, providing a dataset describing the spatial and temporal evolution of the landslide-generated waves. In addition to providing validation data for numerical models, these experiments provide insights into the interaction between the moving landslide and the generated waves.

Method

The experiments were conducted in a flume of length 14.66 m, width 0.25 m and depth 0.5 m. A (horizontal) false floor extended over the length of the flume, reducing the working depth by approximately 80 mm. The landslide moved along a slotted section of this false floor in the central 5 m of the flume, generating waves which propagated in the onshore and offshore directions (where landslide motion is in the offshore direction). The landslide motion was limited to the central 5 m of the flume to achieve a reasonable compromise between the landslide runout distance and the time taken for generated waves to reach the ends of the flume. Reflection of these waves into the wave field effectively ended the experiment. Figure 1 shows the experimental setup, and additional details are provided in Whittaker et al. [7].

The semi-elliptical landslide block was connected to a toothed timing belt through a slot in the false floor, which was in turn connected to a servo motor via a smaller belt located outside of the flume. The landslide motion consisted of three phases: an initial constant acceleration from rest, followed by a 2 s period of constant velocity, followed by a deceleration to rest (at the same rate as the initial acceleration). The landslide motion is therefore defined by its initial acceleration a_0 and its terminal velocity u_t, which may be expressed as a nondimensional acceleration λ and the landslide Froude number Fr:

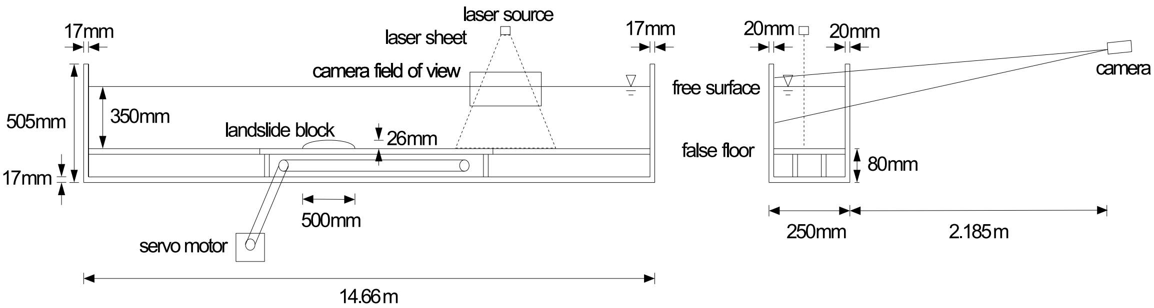

Figure 1: Experimental flume setup, allowing the landslide to move over the false floor in the central 5 m of the flume. Wave amplitudes are measured using an application of laser-induced fluorescence (LIF), with images recorded by a camera located outside of the flume.

Test no.	λ	Fr
1	0.051	0.125
2	0.051	0.250
3	0.051	0.375
4	0.051	0.500
5	0.102	0.125
6	0.102	0.250
7	0.102	0.375
8	0.102	0.500
9	0.153	0.125
10	0.153	0.250
11	0.153	0.375
12	0.153	0.500

Table 1: Parameter space explored in the physical experiments, to investigate the effect of the landslide motion on the generated waves.

$$\lambda = \frac{a_0}{g}, Fr = \frac{u_t}{\sqrt{gD}}, \tag{1}$$

where g is the gravitational acceleration and D is the water depth. In these experiments, the water depth (above the false floor) was 0.175 m. This water depth can be expressed in nondimensional form using the landslide length L, such that:

$$\tau = \frac{D}{L}. \tag{2}$$

The water depth of 0.175 m therefore corresponds to a nondimensional depth of $\tau = 0.35$. Three nondimensional accelerations and four landslide Froude numbers were tested in these experiments, as summarised in Table 1. The servo motor provided highly repeatable motion, and the landslide was able to achieve its velocity targets to within an accuracy of $\pm 5\%$ over the parameter space [7].

The water within the flume was pre-mixed with a small amount of Rhodamine B fluorescent dye. A 532 nm laser illuminated the water from above during the experiments, causing the dye to fluoresce. A camera captured images of the interface between the bright water and dark air from outside of the flume. The camera was angled slightly downwards to avoid meniscus effects at the flume sidewall. Post-processing of the recorded images enabled identification of the free surface elevation to sub-pixel accuracy based on a threshold intensity criterion. Each recorded image had a width of approximately 350 mm, such that experiments needed to be repeated 37 times to capture free surface elevations over the length of the flume. The laser and camera were mounted on a gantry controlled by a servo motor, allowing accurate and repeatable positioning along the flume length, and the camera start times were synchronised by a light-emitting diode (LED) that shone upon initiation of the landslide motion.

The ability to repeatably control the landslide motion and measure spatial and temporal variations in free surface elevation make the experimental dataset valuable for model validation and calibration. However, certain aspects of the experimental wave flume departed from the idealised fluid mechanics problem of a solid block moving along a horizontal boundary. A small exchange flow could occur through the slot in the false floor, possibly allowing some 'leakage' of energy from the landslide-generated wave field. The ends of the flume were not perfectly reflective walls, due to the flume's filling mechanism, and the sidewall boundary may have led to additional energy losses. A more detailed discussion on model effects is provided in Whittaker et al. [7].

Results

Wave field evolution - spatial and temporal information

Figure 2 shows the evolution of the generated wave field in Tests 9-12, i.e. those tests conducted with the highest landslide acceleration of $\lambda = 0.153$ ($a_0 = 1.5$ m/s^2). The distance along the flume is plotted on the horizontal axis, the time after the initiation of landslide motion on the vertical axis and the wave amplitude represented by the colour scale. A solid line represents the location of the landslide centre of mass, and the dashed horizontal lines show the times of motion change from constant acceleration to constant velocity, constant velocity to deceleration and deceleration to rest. Due to the strong dependence of the wave amplitudes on the landslide Froude number, each of the four sub-plots uses a different colour scale.

The intial landslide acceleration generated an offshore-propagating crest and onshore-propagating trough; these waves dominated the wave field at low Fr. Rather than propagating as shallow-water or solitary waves, these leading waves showed weakly dispersive behaviour as they propagated along the flume and attained their maximum amplitude close to $x = 0$ m. The spatial dependence of these maximum amplitudes demonstrates the value of a dataset able to resolve the free surface in both space and time, as discrete measurements may not always measure the maximum amplitudes of dispersive water waves.

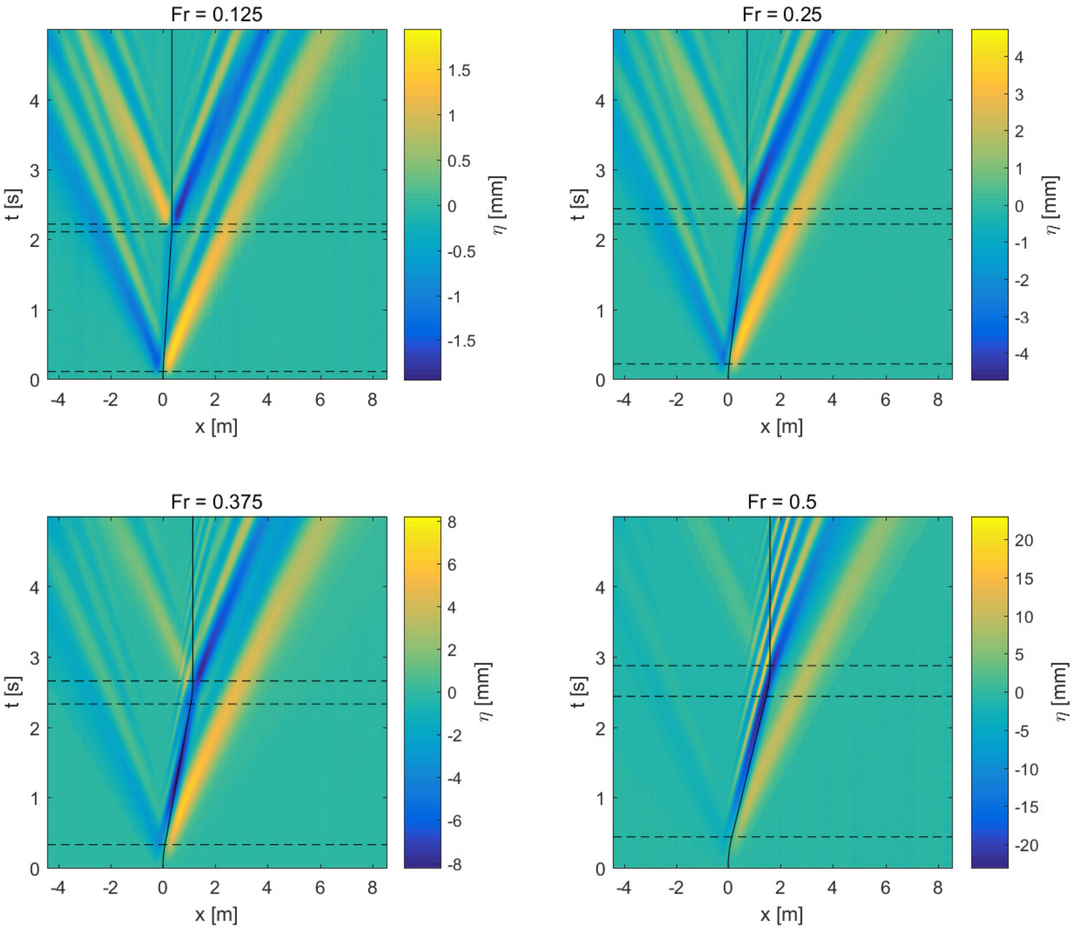

Figure 2: Effect of Froude number on wave field evolution for experiments conducted with an acceleration of $a_0 = 1.5$ m/s^2 ($\lambda = 0.153$) and water depth $D = 0.175$ m ($\tau = 0.35$).

Both onshore- and offshore-propagating leading waves were followed by a dispersive wave train. The offshore-propagating waves propagated over the landslide, creating the possibility of ongoing interactions between the waves and the landslide during its constant-velocity motion. A free surface depression propagated in the low-pressure region above the moving landslide. This is consistent with the open channel flow analogy of a subcritical flow over a submerged hump. The offshore-propagating dispersive wave train were affected by this depression as they passed over the moving landslide, with crest amplitudes being slightly reduced (and trough amplitudes slightly increased) by the depression.

Effects of landslide motion on wave field evolution

The landslide Froude number was the dominant parameter affecting the both the amplitudes and the overall evolution of the wave field, although the initial landslide acceleration affected the amplitudes of the leading waves. It should be noted that this result for a horizontal bottom boundary differs from the sloping-boundary case, where the initial landslide acceleration generates the largest waves in shallow water [6]. Figure 3 shows the effect of the landslide Froude number on the wave field evolution for Tests 9-12, repeated with a longer period of constant velocity (so that the deceleration did not occur within the 5 s measurement period).

At the lower Froude numbers, the wave field was dominated by those waves generated during the landslide acceleration. However, as the Froude number increased the interactions between the offshore-propagating waves and the landslide became relatively more important. The depression above the landslide became larger than the leading onshore-propagating trough above $Fr = 0.125$. Additionally, the landslide was able to transfer energy into those trailing waves within a narrow wavelength band, with phase velocity approximately equal to the landslide terminal velocity u_t. New waves were generated at the rear of the (dispersive) group, which therefore grew over time. These trailing waves had larger amplitudes than the leading waves at $Fr = 0.5$, and broke at larger Froude numbers.

Importance of dispersion and nonlinearity

These results indicate the importance of dispersion and nonlinearity for wave generation by a solid block over a horizontal boundary, particularly at high Froude numbers. Shallow-water theory is unable to describe the behaviour of the leading waves or the interactions between the landslide and the short-wavelength trailing offshore-propagating waves. Linear wave theory underestimates the amplitudes of the generated waves, and does not correctly predict the behaviour of the offshore-propagating waves in the vicinity of the landslide.

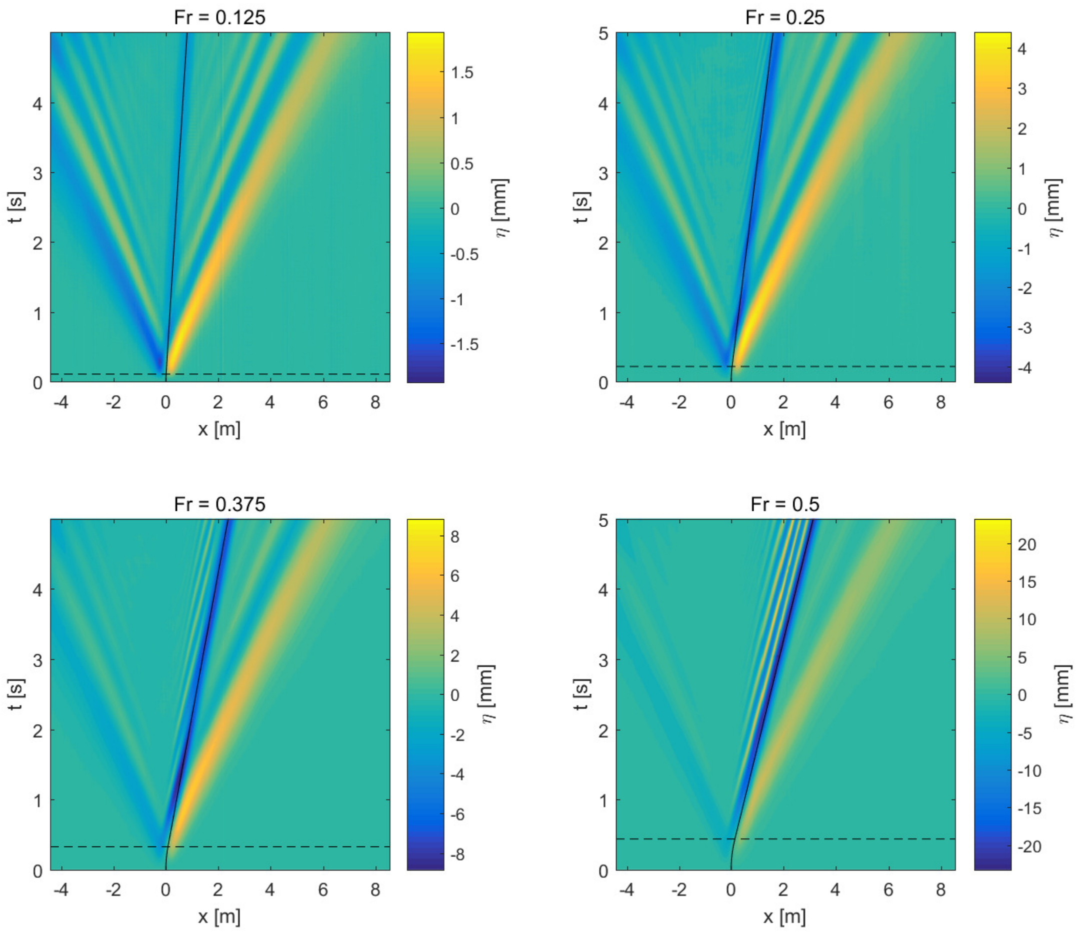

Figure 3: Effect of Froude number on wave field evolution for experiments using the same parameters as in Figure 2, but conducted with a longer constant-velocity phase of motion.

Conclusions

This paper has presented the results of a series of physical experiments investigating the waves generated by the motion of a solid block landslide over a horizontal boundary. The landslide Froude number significantly affected the evolution of the wave field, with the waves generated by the landslide acceleration dominating at low Froude numbers and the interactions between the landslide and the offshore-propagating waves dominating at high Froude numbers. The experimental results provide a robust dataset for model calibration, and indicate that models lacking dispersion or nonlinearity will not adequately describe the generated wave field.

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