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Waves generated by subaerial slides with various porosities

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ABSTRACT

Waves generated by subaerial slides were investigated experimentally in a two-dimensional wave tank. Slide volume, initial position, slope angle and equilibrium water depth were kept constant while the slide material was varied. Five different slide types were employed, one block slide and four granular slides with grain diameter ranging from 3 mm to 25 mm. The slides were accelerated by gravity, with different impact velocities and Froude numbers varying from 0.34 to 0.93. Amplitudes of the generated waves were measured with non-intrusive acoustic wave gauges while the slide position during rundown was recorded with a high speed video camera. Empirical functions for prediction of maximum amplitudes that have been reported in the literature were employed for comparison with the generated waves. Differences between predictions based on the empirical functions and experimental results were discussed together with possible effects of permeability.

1. Introduction

Subaerial and submerged landslides that occur at steep coasts and alpine regions may generate tsunamis which display local wave heights that are larger than even for the largest earthquake generated tsunamis. The tsunami generation process is dependent on the slide dynamics which increases the complexity of the wave generation when compared to earthquake generated tsunamis. The Lituya Bay event, Alaska, in 1958 may be the most famous landslide generated tsunamis in modern time, where an earthquake triggered a landslide which generated a tsunami that over-topped the facing hill up to 520 meters above sea level. This event has been carefully investigated both experimentally and numerically, and good agreement with the historical observations of the real event has been reported (Fritz et al., 2001, 2009; Mader, 1999; Weiss et al., 2009). Another historical event with catastrophic consequences was the huge partially submerged rockslide into the Vaiont reservoir, Italy, where the generated tsunami over-topped the dam and caused almost 3000 fatalities (Semenza and Ghirotti, 2000).

Norway experienced three catastrophic tsunamis generated by rockslides in the twentieth century, in Loen in 1904 and 1936 and in Tafjord in 1934. The runup heights ranged from 41m to 74m and a total of 174 casualties were reported (Harbitz et al., 1993). A future threat is the unstable slope located at Åkneset in Storfjorden, Western Norway. The unstable slope has been thoroughly surveyed for the last decade (Blikra and Kristensen, 2013; Norem et al., 2007) and will eventually produce a slide and subsequent tsunami (Harbitz et al., 2014; Lindstrøm et al., 2014; Sælevik et al., 2009). There are two villages located in Storfjorden, and the fjord is also one of the most tourist visited fjords in Norway so the consequences of a tsunami may be disastrous.

A hypothetical future event is the collapse of a partially submerged flank at La Palma. Ward and Day (2001) brought attention to this event when they reported estimates of wave heights of 900m caused by a 500km^3 slide. The probability of a simultaneous release of such a large volume has been questioned (Masson et al., 2006; Wynn and Masson, 2003). But still, if a tsunami is generated at La Palma it will propagate over the entire Atlantic ocean and affect not only regions close to Canaries Islands but also the entire east coast of North America (Abadie et al., 2012; Gisler et al., 2006; Tehranirad et al., 2015). During the earthquake at Haiti in 2010, two independent tsunamis were triggered by partially submerged landslides and three people were killed. Field surveys reported tsunami heights of only 3 m, which is a reminder that also small landslides may be fatal (Fritz et al., 2013).

Slide generated waves have been investigated for decades, one early work is Wiegel (1955) who did experiments where the slide was represented as a wedge shaped box. Traditionally, investigations regarding slide generated impulse waves seem to be restricted to either block slides or granular material with uniform diameter. During the investigations governing parameters like slide volume,

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impact velocity, impact angle and slope angle are usually varied. Experimental investigations provide valuable information for the understanding of real events, including estimations of critical parameters such as maximum wave heights and runup. The experimental results may also serve the purpose of a benchmark for developing numerical models.

Slide properties are critical for prediction of generated waves for real events, and there are often uncertainties connected to whether the slide will consist of one or a few large blocks or more granular material. Normally the slide masses will deform during rundown and impact in a highly complex manner, dependent on the slide material. Newer investigations address the variety of slides by applying different kinds of slide masses and shapes. Ataie-Ashtiani and Nik-Khah (2008) conducted quasi-2D experiments where they employed both granular and block slide models, they reported 120 tests where slide volume, thickness, length, rigidity, angle, initial position and still water depth were varied. Heller and Spinneken (2013) included blockage ratio, slide front angle and transition type at the slope end in their work on block slide generated waves, and reported empirical equations for the properties of the generated waves. Heller and Spinneken (2013) also discussed block slide generated waves in comparison with waves generated by granular slides. Bolin et al. (2014) investigated waves generated by granular clusters and rigid blocks, where they varied the bed slope angle, water depth, impact velocity, slide geometry and slide volume. Viroulet et al. (2014) investigated different granulates running down an inclined plane with rough surface, they addressed cliff failures just above the surface and worked with low Froude numbers. Viroulet et al. (2014) reported that the interplay between fluid and slide during its collapse still is a remaining problem that requires further work. Evers and Hager (2015) compared mesh-packed slides with free granular slides, with the conclusion that mesh-packed slides give approximately the same results as free granular slides. Heller and Kinnear (2010) discussed differences between block and granular slides, based on seven governing parameters: still water depth, slide impact velocity, slide thickness, slide volume, bulk slide density, slide front angle and grain diameter. They claimed that there were five distinct differences between the two slide types, namely: Porosity, slide front angle, blockage ratio, transition between slope toe and channel bottom and rigidity.

In nature, landslides are typically a mixture of large and smaller blocks, clusters of gravel and sand. Therefore, we wish to investigate the differences of waves generated by slides with the same volume but different slide components. Present work is based on experiments conducted in a two-dimensional wave tank where the slide material and grain size are varied. Our focus are the generated waves, where the maximum amplitude in the wave envelope is of particular interest due to hazard assessment.

2. Governing parameters

Wavefields that are generated by slides are dependent on a number of different parameters, such as impact velocity v_i, slide geometry, slide mass m_s, slide volume V, porosity, slope angle α, slide front angle ϕ and equilibrium water depth h. Parameters that are considered to be dominant in the wave generation may be described by a set of dimensionless parameters such as Froude number $F = v_i/\sqrt{gh}$, where g is gravitational acceleration and $\sqrt{gh}$ is wave celerity of shallow water waves. $S = s/h$ is the relative slide thickness and $M = m_s/(\rho_w b_s h^2)$ describes the relative slide mass where ρ_w is density of water and b_s slide width. Empirical functions that describe wave features may be established in terms of the dimensionless parameters, where the functions are constructed by multiple regression of the experimental results. These functions may then be used to predict real-world events, typically maximum amplitudes, wave heights and periods.

2.1. Estimates of maximum amplitude in two-dimensional facilities

Fritz et al. (2004) conducted a large number of granular slide experiments in a two-dimensional wave tank. They varied the slide mass, slide impact velocity, still water depth and slide thickness. The granular slide material had a grain with diameter of 4mm, which was kept constant during the investigation. Fritz et al. (2004) found that the Froude number and relative slide thickness were the dominant parameters for classification of the generated waves and estimation of the maximum amplitude in the generated wavefield. They reported an empirical equation for the maximum amplitude, a_c, of the generated wavefield

$$\frac{a_c}{h} = 0.25F^{1.4}S^{0.8} \tag{1}$$

which was computed by multiple regression of their experimental results.

Zweifel et al. (2006) conducted experiments on 4mm diameter granular slides, where they varied the same parameters as Fritz et al. (2004). In addition the densities of the granular slides were varied by using four composites of two granulates with different density, also covering snow avalanches where the slide density is smaller than the density of water. They reported that the Froude number was the dominant parameter for slow impacting slides, while for large Froude number slides the equilibrium depth and slide thickness had to be included. They applied an empirical relation for the maximum amplitude

$$\frac{a_c}{h} = \frac{1}{3}FS^{1/2}M^{1/4} \tag{2}$$

which included the dimensionless slide mass in addition to Froude number and relative slide height.

In the experimental work of Heller and Hager (2010), the slide was represented by granular material with grain with diameters varied between 2 and 8mm and density varied between 0.955 and 2.745 g/cm^3. They reported an empirical impulse product parameter P which included the Froude number, relative slide thickness, relative slide mass and slope angle

$$P = FS^{1/2}M^{1/4}\left(\cos\left(\frac{6}{7}\alpha\right)\right)^{1/2} \tag{3}$$

This parameter was used to predict the wave characteristics, where the maximum amplitude for granular slides was reported as

$$\frac{a_c}{h} = \frac{4}{9}P^{4/5} \tag{4}$$

Later on, Heller and Spinneken (2013) employed the same impulse product parameter for block slides, and reported an empirical relationship based on their experimental results of maximum amplitudes and wave heights by including the blockage slide ratio, transition between slope and bottom and slide front angle in the equations.

$$\frac{a_c}{h} = \frac{3}{4}\left(PB\Phi T_s^{1/2}\right) \tag{5}$$