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Impulse waves generated by subaerial landslides of combined block mass and granular material

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A B S T R A C T

Experimental results, based on two-dimensional (2-D) laboratory tests, for impulse waves generated by subaerial landslides of combined solid block and granular materials are presented in this study. The results are compared with those of individual models of pure solid block and granular landslides. By considering an identical slide mass and release height, the effect of the mass ratio m^* on wave generation was investigated. The mass ratio is defined as $m^* = M_B/M$, where M_B is the mass of the solid block, $M = M_B + M_G$ is the total mass and M_G is the mass of the granular portion. The experimental results show that the combined landslides with $m^* = 0.6$ and 0.8 in this study generally produce much larger impulse waves in the impact zone compared with those triggered by pure solid block landslides ($m^* = 1$) and pure granular landslides ($m^* = 0$). This suggests that the primary wave amplitudes of impulse waves might have been underestimated in previous laboratory tests with solely solid or granular assemblies when using the same slide mass and release height. The larger primary wave amplitudes of the combined landslides compared with those of the pure solid block landslides are mainly attributed to the relatively large thickness of the combined landslides and the continuous motion of the granular portion, as the inside solid block stops at the hill slope toe. Compared with pure granular landslides, combined landslides generally have a larger Froude number and slide thickness, which account for the larger primary wave amplitudes. The latter plays a quantifiably more important role – nearly two times that of the former. The effects of the hill slope angle α, and the grain size of the granular materials D, were also studied in this work. Four different hill slope angles ($\alpha = 22.5^\circ$, 30°, 37.5° and 45°) and four different mean grain diameters ($D = 5$ mm, 10 mm, 20 mm and 30 mm) were tested. By comparing the measured maxima of the wavelet spectra obtained via a wavelet transform method with those reconstructed by means of the phase celerity of the solitary wave c_s and the group celerity of linear wave $c_g(f)$, it is found that the measured maxima travel at either c_s or $c_g(f)$, depending on the landslide type and the hill slope angle α. However, the celerity of the measured maxima for the high frequency is lower than $c_g(f)$ and c_s for the impulse waves generated by combined landslides when $\alpha \le 37.5^\circ$ in this study. Further investigations show that the wave amplitude decreases rapidly during wave propagation, following an exponential function. The decrease in the wave amplitude during propagation is mainly attributed to dispersion.

1. Introduction

Subaerial landslides can trigger large-amplitude water waves in confined water bodies, such as reservoirs and lakes. These kinds of water waves are normally known as impulse waves. They may propagate a long distance from the impact zone and run up the coastline or over the top of artificial structures, causing serious disasters and threatening the safety of engineering structures. In some cases, such as in Lituya Bay, Alaska, in 1958, the impulse waves generated by landslides are the main hazard (Miller, 1960; Fritz et al., 2001, 2009; Weiss et al., 2009; Xenakis et al., 2017). In the event of Lituya Bay, the generated impulse waves destroyed the forest to a run-up height of 524 m above the mean sea level (Miller, 1960). Hence, a better understanding and prediction capability for impulse waves, together with their propagation and deformation, are of great importance for reducing potential hazards (Di Risio et al., 2009a).

For subaerial landslides, the generation of impulse waves is a complex dynamic process, involving interactions among three different phases (solid, liquid and air). Focused on this issue, a number of experimental studies have been carried out so far. Traditionally, real landslides are generally modelled as either solid block landslides or granular landslides – for example, Heller and Hager (2010), Heller and

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Spinneken (2013), and Evers and Hager (2015), among others. Wiegel (1955) was among the first to investigate the impulse waves induced by block landslides. The effects of the slide mass, the water depth, the slide length and the hill slope angle on impulse waves were studied. Wiegel (1955) reported that the primary wave amplitude increases with an increase in water depth, slide mass and hill slope angle. The increase in the slide length mainly results in an increase in the initial wave period (namely, the time interval between the first and second wave crests), while the slide length has a weak influence on the primary wave amplitude. Noda (1970) carried out laboratory tests to study impulse waves by sliding block landslides down a flume. Four different impulse wave patterns were identified according to the water depth, the slide volume and the momentum exchange between the water body and the block landslide. The work conducted by Kamphuis and Bowering (1970) showed that the slide impact velocity and the slide volume are the controlling parameters for the primary wave amplitudes. A series of 2-D experiments were performed by Walder et al. (2003) to investigate the near-field properties of impulse waves. The slide impact velocity, the submerged time of the slide motion and the slide volume were identified as the relevant parameters for impulse waves. Liu et al. (2005) studied impulse waves through both experimental and numerical approaches. In their experiments, a block landslide was represented by a wedge. They observed that subaerial landslides can lead to significantly larger wave run-up than submerged landslides. The wave runup and rundown were mainly controlled by the size and motion of the landslide. Dong et al. (2010) carried out experiments to investigate the harbour resonance induced by impulse waves. The impulse waves were triggered by dropping a rigid block vertically from the still water level into the water body. The generated waves were classified into solitary waves and dispersive waves based on the slide volume. Heller and Spinneken (2013) reported that the primary wave amplitude, the wave height, and the wave period in the impact zone and during propagation were strongly related to the slide Froude number, the relative slide mass and the relative slide thickness. Based on their experimental studies, Heller and Spinneken (2013) proposed an empirical formula to predict the generated impulse waves. In their later work, Heller and Spinneken (2015) conducted three-dimensional (3-D) laboratory tests to study impulse waves. By comparing their 3-D and 2-D experimental results, a useful method was developed to transform 2-D predictions into 3-D situations for impulse waves generated by block landslides. When impulse waves are triggered in the impact zone, especially in the shallow water region, the waves generally behave as tsunamis. It is also important to ascertain the wave deformations in order to prevent serious damage. This topic has also attracted much attention in the past, for example, in the works by Panizzo et al. (2002), Panizzo and Girolamo (2005), Sammarco and Renzi (2008), Di Risio et al. (2009b) and Dong et al. (2010), among others.

In addition to the above investigations, many researchers have paid attention to the impulse waves generated by granular landslides. Fritz and Moser (2003) developed a pneumatic landslide generator to investigate the landslide-generated impulse waves. They identified the granular slide mass, the slide impact velocity, the water depth and the slide thickness as the governing parameters of wave generation. Aiming at impulse wave generation and propagation, 2-D laboratory tests were conducted by Fritz et al. (2003a; 2003b). A particle image velocimetry (PIV) technique was employed to examine the interaction between a granular landslide and a water body. Empirical formulae for predicting the impulse wave amplitude, the wave period, the wave length and the wave celerity were derived. Based on 2-D experimental results (Fritz et al., 2004), the generated waves were divided into four patterns according to the slide Froude number and the slide thickness, namely, a weakly nonlinear wave, a nonlinear transition wave, a solitary-like wave and a dissipative transient bore. Zweifel et al. (2006) systematically examined the influences of the slide impact speed, the water depth, and the slide thickness on impulse waves. Zweifel et al. (2006) reported that the slide Froude number is the controlling parameter for slowly impacting slides. However, for landslides with large Froude numbers, the primary wave amplitudes are dependent on the water depth and the slide thickness in addition to the slide Froude number. The findings of Zweifel et al. (2006) at large Froude numbers are consistent with the observations by Fritz (2002) and Fritz et al. (2004), who also found that both the slide Froude number and the slide thickness have significant influence on the primary wave amplitudes. Heller et al. (2008) showed that the impulse waves can be investigated experimentally by using the Froude similarity. They identified the slide Froude number, the relative slide mass and the relative slide thickness as the governing parameters for the primary wave amplitudes. Accordingly, an impulse product parameter was proposed by Heller and Hager (2010) to predict the generated impulse waves. The primary wave amplitude, the wave period and the wave amplitude decay with the wave propagation were quantified based on the impulse product parameter. Later, they extended the impulse product parameter to the situation of block landslides (Heller and Spinneken, 2013) and found that the impulse product parameter is a useful and effective parameter for predicting real-world impulse waves (Heller and Hager, 2014). Recently, Evers and Hager (2015) compared the wave amplitude, the wave height and the wave decay between free granular slides and mesh-packed granular slides. They found that mesh-packed landslides led to results similar to those of free granular landslides. Mohammed and Fritz (2012, 2013) conducted 3-D laboratory tests to investigate impulse waves. In their tests, the granular landslides were composed of rounded river gravel. The particle size ranged from 6.35 mm to 19.05 mm, with a median grain size diameter of d_{50} = 13.7 mm. Empirical formulae for predicting the wave amplitude, the wave period and the wavelength were proposed. They found that the landslide Froude number is the dominant parameter. McFall and Fritz (2016) also experimentally studied the impulse waves triggered by granular landslides. In their experiments, the landslides were released on both planar and conical island slopes, and the effect of the hill slope was examined. Two landslide materials were used there. One was naturally rounded river gravel, with a grain size gradation of 95% passing through a 19.1 mm sieve and 5% passing through a 12.7 mm sieve. The mean grain size diameter was d_{50} = 13.7 mm. The other was naturally rounded river cobble, with a grain size larger than 19.1 mm; the sizes of some cobbles were even larger than 100 mm. The experimental results showed that a cobble landslide could deliver, on average, 43% more kinetic energy into the generated waves than a gravel landslide. Recently, the wave runup and rundown were investigated based on 3-D landslide experiments (McFall and Fritz, 2017). Empirical formulae for predicting the wave runup and rundown inside and outside of the impact zone were proposed.

Our literature survey suggests that previous investigations have generally focused on the impulse waves generated by either block landslides or granular landslides. However, in nature, a landslide may be composed of both solid block and granular materials. The resultant impulse waves might change notably depending on the combination of block and granular mass. However, to the best of our knowledge, less attention has been given to this issue. Therefore, the present experiments were designed and conducted to fill this gap. The objectives of this work are to 1) investigate the dependence of the primary wave amplitude on the mass ratio, hill slope angle and grain size; 2) compare the primary wave amplitudes generated by combined landslides with those generated by pure solid block and granular landslides; and 3) examine the celerity and frequency features of the impulse waves during propagation.

The remainder of this article is organized as follows. The details of the experimental set-up are described in Section 2. The experimental results and discussion are presented in Section 3, including comparisons of the impulse waves induced by combined landslides with those produced by pure solid block landslides and pure granular landslides. The effects of the mass ratio, the hill slope angle, and the grain size of granular materials on the primary wave amplitude, the decrease in the wave amplitude during propagation, the wave celerity and the