Coastal Engineering 104 (2015) 113–134

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

On the effect of the water body geometry on landslide–tsunamis: Physical insight from laboratory tests and 2D to 3D wave parameter transformation

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ARTICLE INFO

Article history:
Received 13 March 2015
Received in revised form 2 June 2015
Accepted 13 June 2015
Available online 17 August 2015

Keywords:
Hazard assessment
Impulse wave
Landslide–tsunami
Physical modeling
Water waves
Wave generation

ABSTRACT

Preliminary landslide–tsunami hazard assessment is commonly based on empirical equations derived from wave channel (2D) or wave basin (3D) experiments. The far-field wave in 2D can easily be an order of magnitude larger than in 3D. The present study systematically investigates the effect of the water body geometry on the wave characteristics in the near- and far-field. Subaerial landslide–tsunami tests were conducted relying upon both a 2D and a 3D physical model, undertaken with identical boundary conditions. The test parameters included two water depths, three rigid slides, as well as various slide release positions. Empirical equations for 3D offshore and laterally onshore wave properties are presented and compared with previous work. A direct comparison of the wave features reveals that the waves decay in 2D, 3D onshore and 3D offshore with $x^{-0.30}$, $r^{-0.67}$ and $r^{-1.0}$, where x (2D) and r (3D) describe the distance from the impact zone. In 2D four wave types are observed, whereas only the two least non-linear types were observed in 3D. This finding is further analysed with wavelet spectra. For a large slide Froude number F, relative slide thickness S and relative slide mass M, the 3D wave heights in the slide impact zone can be as large as in 2D. However, for small F, S and M, the 3D waves are considerably smaller both in the near- and far-field. A novel method is presented and validated to transform data from 2D studies to 3D. This method may have favourable implications on preliminary landslide–tsunami hazard assessment.

1. Introduction

1.1. Overview

Landslide–tsunamis are generated by mass movements such as landslides, slumps, debris flows, rock falls, asteroid impacts, shore instabilities or glacier calving interacting with a water body. They are particularly relevant for regions or mountainous countries such as Austria, Canada, China, Denmark (Greenland), Lesser Antilles (Montserrat), Norway, Spain (Canary Islands), Switzerland or Turkey. Such waves occurred, for instance, in the Lituya Bay, Alaska, in 1958 destroying the forest up to a run-up height of 524 m (Miller, 1960) or in Papua New Guinea in 1998 with 2100 casualties (Synolakis et al., 2002). If a mass slides into a confined water body such as a reservoir or lake, in similarity to the 1963 Vajont catastrophe with a death toll of about 2000 (Müller, 1964), the waves are referred to as impulse waves. Many further examples of landslide–tsunamis and impulse waves covered in the reviews of Slingerland and Voight (1979), Huber (1982) and Masson et al. (2006) are a reminder of how frequently such waves occur, and of the considerable risk they may pose for humans and infrastructure. For the remainder of this paper, the terms landslide–tsunamis and impulse waves will be used as interchangeable terms to describe the types of events outlined above.

Landslide–tsunamis need to be reliably predicted on many occasions. Such occasions include the planning and operation phases of reservoirs (Fuchs et al., 2011), or more generally when a slide located above, or partially above, a water body starts to creep such as in the Vajont case (Müller, 1964). Measures to deal with landslide–tsunamis are mainly limited to passive methods such as early warning, evacuation, reinforced infrastructure, safety clearance from ice calving prone areas, reservoir drawdown or provision of adequate freeboard of dam reservoirs. These measures are mainly available for subaerial cases, since mass instabilities are more easily noticed and monitored than for underwater masses. An exact prediction of the wave features is crucial for these passive methods, and such predictions have to be conducted quite frequently during the planning and operational phases of reservoirs, in fiords, lakes or the sea.

Empirical equations developed from generic model studies prove to be popular in dealing with landslide–tsunamis. Generic model studies systematically vary parameters (slide properties, hill slope angle,

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http://dx.doi.org/10.1016/j.coastaleng.2015.06.006
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water depth) which may be estimated a priori for real-world events, and express the unknown wave parameters (amplitude, height, period) as a function of these parameters. The resulting empirical equations can be very efficient in predicting future events (Heller et al., 2009), and are often the most straightforward method if time is limited. At the very least, such equations can help to determine whether or not a prototype specific numerical (Abadie et al., 2012; Løvholt et al., 2008) or physical (Davidson and Whalin, 1974; Fuchs et al., 2011) model study is required. These latter methods are both considerably more expensive and time consuming than applying generic empirical equations.

Generic model studies are conducted under idealised conditions which often concern the slide properties. Perhaps more importantly, idealisations also apply to the geometry of the water body, which is commonly represented by a wave channel (2D) or a wave basin (3D). Both types of geometries have their justification in real-world applications, and may be considered as two extreme cases of naturally occurring geometries (Heller et al., 2009):

(i) 2D: The slide impacts longitudinally; the slide (subscript s) width b_s being identical or larger than the water body width b. The waves are confined as they move along x, the longitudinal direction of the water body, without transverse or radial spreading.
(ii) 3D: The slide, with a width $b_s < b$, impacts into a larger water body. The waves propagate laterally and radially from the slide impact zone, and can be described in cylindrical coordinates with the radial distance r and the wave propagation angle γ.

Tests in 2D are generally more cost efficient, less time consuming and allow better optical access, such that landslide–tsunamis are considerably better investigated and understood in 2D than in 3D. This is reflected in the large number of generic studies investigating subaerial landslide–tsunamis in 2D such as Noda (1970), Wiegel et al. (1970), Kamphuis and Bowering (1972), Slingerland and Voight (1979), Huber and Hager (1997), Monaghan et al. (2003), Walder et al. (2003), Fritz et al. (2004), Quecedo et al. (2004), Liu et al. (2005), Lynett and Liu (2005), Panizzo et al. (2005), Zweifel et al. (2006), Ataie-Ashtiani and Nik-Khah (2008), Heller et al. (2008), Sælevik et al. (2009), Abadie et al. (2010), Heller and Hager (2010, 2011), Fuchs et al. (2013) and Heller and Spinneken (2013). The number of generic studies conducted in 3D is considerably smaller, with Huber and Hager (1997), Liu et al. (2005), Panizzo et al. (2005) and Mohammed and Fritz (2012) as main contributors. Unfortunately, existing 3D studies often exclude the splash zone data, which is considered an important part of the problem for confined water bodies.

1.2. Review on the effect of the water body geometry

Chang et al. (1979) investigated experimentally and numerically generated solitary waves in both linear converging and diverging wave channels of side wall angle $\theta = 1.1°$. For relative distances $x/h < 40$, the wave heights H_2 observed at one cross section 2 (subscript 2) is well approximated as a function of H_1 at section 1 (subscript 1) with

$$H_2/H_1 = (h_1/h_2)^{1/4}(b_1/b_2)^{1/2}. \tag{1}$$

For constant channel widths $b_1 = b_2$, this latter equation is better known as Green's law, which is based on the concept of energy flux conservation in shallow water of depth h. Chang et al. (1979) further observed that, for larger x/h and a diverging channel, the decay is underestimated by Eq. (1) due to viscous damping. Several studies also showed that Eq. (1) has its limitations if applied to solitary or solitary-like waves (Heller et al., 2012; Synolakis and Skjelbreia, 1993).

In investigating tsunamis based on submarine mudslides, Jiang and LeBlond (1994) developed a numerical model using long-wave theory; the fluid being assumed to be inviscid and irrotational. They found that the difference between 2D and 3D depends on the slide width to length ratio b_s/l_s. For small b_s/l_s, significant differences were found between 2D and 3D. In contrast, for large b_s/l_s, the deviations between 2D and 3D were found to be small; this being attributed mainly to the transversal spreading of wave energy in 3D.

Watts et al. (2005) investigated submarine landslide generated tsunamis. In the proximity of the wave generation zone they provide an approximation for the maximum (subscript M) wave amplitude in 3D, $a_{3D,M}$, as a function of the maximum wave amplitude in 2D, $a_{2D,M}$, as

$$a_{3D,M} = a_{2D,M}[b_s/(b_s + L_0)], \tag{2}$$

where L_0 is the characteristic wave length. This equation shows that the difference between 2D and 3D is small for a large ratio b_s/L_0, whereas the difference may reach an order of magnitude or more for a small ratio b_s/L_0. This is consistent with the findings of Jiang and LeBlond (1994) noted above.

Kranzer and Keller (1959) showed analytically that the wave amplitude decays differently in 2D, with $x^{-1/3}$ to $x^{-1/2}$, compared to 3D, with r^{-1}. Similar analytical results are shown by Løvholt et al. (2008). They found a 2D wave height decay ranging from $x^{-1/3}$ (for a monopole-like source) to $x^{-2/3}$ (for a dipole-like source). In 3D, the corresponding wave height decays were found as $r^{-5/6}$ to $r^{-7/6}$. Løvholt et al. (2008) also compared these 3D decays with Boussinesq model simulations of the potential Cumbre Vieja volcano slide at La Palma, establishing a good agreement.

It is important to note that most 2D experimental subaerial landslide–tsunami studies tend to result in smaller wave amplitude or height decays than theoretically predicted. Examples of this are provided by Wiegel et al. (1970) with $a_{2D}(x) \propto x^{-1/5}$, Heller and Hager (2010) with $a_{2D}(x) \propto x^{-4/15}$ or Heller and Spinneken (2013) with $a_{2D}(x) \propto x^{-3/10}$. The experimentally deduced variation is similarly large for 3D studies namely $a_{3D}(r) \propto r^{-19/20}$ in Davidson and Whalin (1974), $H_{3D}(r) \propto r^{-2/3}$ in Huber and Hager (1997), $H_{3D}(r) \propto r^{-0.81}$ in Panizzo et al. (2005) and up to $a_{3D}(r) \propto r^{-1.42}$ in Abadie et al. (2012). The decay may also differ for the primary and secondary wave (Panizzo et al., 2005).

An extensive and systematic comparison of 2D and 3D subaerial landslide generated impulse wave experiments was presented by Huber (1980). The data included approximately 1000 2D and 150 3D granular slide experiments, which were partially re-analysed by Huber and Hager (1997). The wave height H decays with $x^{-1/4}$ for $x/h \leq 100$ and with $r^{-2/3}$ for $r/h \leq 30$. Huber (1980) states that H between 2D and 3D deviates little from each other near to the slide impact zone such that $H_{3D}(x/h = 5) = H_{2D}(r/h = 5)$ was assumed. Adopting this assumption, Huber and Hager (1997) developed a 3D prediction formula. This formula relies on a 3D data set as well as a generalisation of 2D observations to 3D.

This 2D to 3D transformation method was adopted by Heller et al. (2009) to transform 2D prediction formula for subaerial landslide–tsunamis to 3D and to provide a method to predict their effects including run-up heights, overtopping volumes and forces on dams in reservoirs. Several case studies (e.g. Battaglia et al., 2015; Fuchs and Boes, 2010), showed that the wave features are accurately and efficiently predicted by applying Heller et al. (2009). However, generally speaking, the results appear to lie slightly on the conservative side (over-estimation of wave amplitude and height) in 3D applications.

In seeking to improve the reliability of the method by Heller et al. (2009), Heller et al. (2012) conducted a small scale physical model study. This latter study was conducted with one rigid slide scenario, resulting in a solitary-like wave. The wave was generated in different geometries including 2D, 3D and five intermediate geometries with diverging side walls. Heller et al. (2012) showed that the 2D and 3D wave amplitudes deviate by a factor of 6.7 after a relatively short distance $r/h = 12.5$. The wave height $H_{3D}(r/h = 5)$ is about 20% smaller than $H_{2D}(x/h = 5)$ such that the assumption $H_{3D}(x/h = 5) = H_{2D}(r/h = 5)$ of Huber and Hager (1997) is believed to overestimate