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Optimization model for maximum tsunami amplitude generated by riverfront landslides based on laboratory investigations

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ABSTRACT

Riverfront landslides often occupy rivers and cause tsunamis as they move into the water body in a direction perpendicular to the channel axis. The tsunami amplitude is undoubtedly affected by the dimension of landslide and river. This paper presents a study examining the relationship between the maximum tsunami amplitude and the volume ratio, which is defined as a ratio of landslide volume per unit width to the water body volume per unit width. Physical model tests have been conducted for maximum tsunami amplitudes generated by riverfront landslides. The orthogonal experimental design method is used for the determination of the number of required trials. The 49 runs, possessing a level number of 7 and a factor number of 6, are chosen to consider symmetrical distribution of all factors using the orthogonal experimental design method. The Levenberg–Marquardt method is applied to carry out multiple regressions, and the most optimal model is obtained by the determination coefficient, the mean square error and F-statistic. Case studies show that the calculated maximum tsunami amplitudes are 11.7% larger than their actual values on average.

1. Introduction

Landslides, or submarine mass failures, are currently thought to be one of the major mechanisms for tsunami generation in riverfront or coastal areas (Ma et al., 2013). Tsunamis generated by landslides pose a very dangerous threat to dam structures, agricultural areas, coastal properties, and human communities living on the shorelines of seas, rivers and artificial reservoirs (Panizzo et al., 2005b; Huang et al., 2014). A number of catastrophic tsunamis caused by subaerial and partially submerged landslides are well-known from observations in Norway, Italy, Japan, USA and many other localities. Their combined documented human death toll probably exceeds 60,000 (Davidson and McCartney, 1975; Slingerland and Voight, 1979; Heller, 2007). One of the most destructive tsunamis occurred in 1963, in Vajont, North Italy where a landslide with a volume of 270 million m^3 slid into a manmade reservoir. The generated tsunami overtopped the concrete dam by more than 70 m destroying everything in its path and killing approximately 2000 people (Müller, 1964; Bosa and Petti, 2011; Heller et al., 2012; Crosta et al., 2016). Norway experienced three major tsunamis due to subaerial rockslides in the twentieth century. A subaerial rockslide with a volume of 1.5 million m^3 occurred on 7 April 1934 in Tafjord, western Norway. The tsunami caused 40 deaths and its runup heights were up to 60 m (Harbitz et al., 1993; Lindstrøm et al., 2014). The Three Gorges Reservoir (TGR) in China also faces the serious situation of landslide-generated tsunamis because there are plenty of unstable landslides along the Yangtze River (Wang et al., 2016). On 12 June 1985, the Xintan landslide, with a total volume of 30 million m^3, slid into the Yangtze River at a speed of approximately 20 m/s and induced a tsunami with wave run-up of 54 m on the opposite shore, causing 10 deaths and destroying 13 ships and 64 wooden boats (Wang, 2009; Wang and Xu, 2009). The tsunami caused by the 13 July 2003 Qianjiangping landslide overthrew 22 boats and killed 11 fishermen in the nearby area (Wang et al., 2004; Liao et al., 2005; Yang and Wang, 2009). The Gongjiafang landslide, which was a rock landslide with a volume of 380,000 m^3, generated a 13 m wave run-up on the opposite bank. The tsunami propagated over 0.4 km to Wushan County, with a 1–2 m wave height, resulting in economic losses of five million RMB (Huang et al., 2012, 2014). Tsunamis generated by landslides are characterized by locally high amplitudes and run-up, which would be particularly devastating for nearby regions and confined water bodies (Okal and Synolakis, 2004; Mohammed and Fritz, 2012). Therefore, the estimation of maximum tsunami amplitude is crucial for predicting the effects of waves on river banks, shorelines or dams.

Landslide-generated tsunamis can be analyzed using general physical model tests, prototype scaled model tests, numerical simulations, empirical equations based on field data, or analytical calculations (Heller and Hager, 2011; Huang et al., 2014). Among these analysis

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Table 1
Governing parameters related to tsunami wave amplitude or wave height.

Types	Parameters	Symbols	Dimensionless symbols
Kinematic parameters	Landslide impact velocity	v	$F = v/\sqrt{gh}$
	Landslide underwater travel time	t	$T = t\sqrt{g/h}$
	Tsunami propagation direction	γ	
Geometric parameters	Landslide thickness	s	$S = s/h$
	Landslide width	w	$W = w/h$
	Landslide length	l	$L = l/h$
	Landslide volume	v_0	$V_0 = v/h^3$
	Landslide volume per unit width	v_1	$V_1 = v_1/h^2$
	landslide front area	v_2	$V_2 = v_2/h^2$
	Water depth	h	
	Landslide impact angle	α	
	River width	b	
	Landslide shape factor		$F_1 = l/s$
	Landslide shape factor		$F_2 = w/s$
Dynamic parameters	Water density	ρ_w	
	Landslide density	ρ_s	$D = \rho_s/\rho_w$
	Landslide mass	m_s	$M = m_s/(\rho_w bh^2)$

methods, model tests can usually obtain detailed characteristics of tsunamis for verifying numerical simulations and analytical calculations (Chaudhry et al., 1983; Najafi-Jilani and Ataie-Ashtiani, 2008). Moreover, laboratory investigations can provide sufficient data to express wave properties as a function of governing parameters, which benefit the quick and straightforward prediction of future tsunami events (Heller and Spinneken, 2013; Huang et al., 2014; Lindstrøm et al., 2014; Wang et al., 2016). The parameters used in the empirical functions are related to kinematics, geometry and dynamics (Table 1). The kinematic parameters consist mainly of landslide impact velocity, landslide underwater travel time and tsunami propagation direction. The geometric parameters primarily consist of landslide thickness, width, length, landslide volume, landslide front area, still water depth, landslide impact angle, river width and landslide shape factor. The dynamic parameters mainly include water density, landslide density and landslide mass.

Many empirical functions were used to understand the effects of governing parameters on the generated maximum wave amplitude or wave height (Table 2). Some earlier experimental investigations showed that maximum wave amplitude is strongly affected by dimensionless landslide velocity (Froude number), dimensionless volume or volume per unit width, and dimensionless slide kinetic energy (Noda, 1970; Kamphuis and Bowering, 1970; Slingerland and Voight, 1979). The importance of Froude number and slide thickness was also determined by Fritz (2002) and Fritz et al. (2004). The impulse product parameter was later proposed as a comprehensive term consisting of the landslide Froude number, the dimensionless landslide thickness, the dimensionless landslide mass and the landslide impact angle (Heller, 2007). Some earlier researches chose vertical and horizontal landslide models to discuss the influences of landslide impact angle on surface gravity waves (Wiegel et al., 1970; Noda, 1970; Das and Wiegel, 1972). However, the effect of the angle on tsunami amplitude is controversial. Huber and Hager (1997) thought that the maximum wave height increased as the angle increased, but Panizzo et al. (2005a) presented an inverse influence. Dimensionless landslide density was taken as another relative variable using an exponential function in some regression equations (Huber and Hager, 1997). The time of underwater landslide motion was noted to be a key parameter for describing the generated tsunami (Watts, 1998; Walder et al., 2003), and also recognized by Panizzo et al. (2005a) and Ataie-Ashtiani and Nik-Khah (2008). Mohammed and Fritz (2012) considered landslide width and landslide length as two separate items. The effect of landslide shape on the wave amplitude was described by defining landslide shape factor, which is the ratio of the landslide length or width to the thickness (Ataie-Ashtiani and Nik-Khah, 2008; Huang et al., 2014). Landslide thickness was considered an important factor of wave amplitude (Fritz, 2002; Fritz et al., 2004; Di Risio, 2005; Zweifel et al., 2006; Heller, 2007; Mohammed and Fritz, 2012; Huang et al., 2014). Compared with the two-dimensional model, the three-dimensional model replaced streamwise distance by the radial distance and the wave propagation direction angle (Huber and Hager, 1997; Panizzo et al., 2005b; Mohammed and Fritz, 2012, 2013; McFall and Fritz, 2016). Xenakis et al. (2017) carefully considered the turbulence in the water phase and soil saturation in the landslide phase. These existing methods usually consider water depth to be an important parameter but rarely take into consideration other geometric parameters of rivers. When a riverfront landslide with the sliding direction perpendicular to the channel axis enters the water body, it occupies the river and causes the tsunami. The cross-section of the river obviously has a significant effect on the tsunami amplitude and consequently is worthy of further consideration.

This paper presents an optimization model for maximum tsunami amplitude generated by riverfront landslides, considering the effect of the dimensions of the river on the maximum tsunami amplitude. The volume ratio is proposed as a new parameter based on the analysis of three landslide-generated tsunami cases. The Levenberg–Marquardt method is used to build the relationship between the maximum tsunami amplitude and the volume ratio, based on the orthogonal experimental design method with six factors at seven levels.

Table 2
Governing parameters used in some previous studies.

Studies	Kinematic			Geometric									Dynamic	
	F	*T*	*γ*	*S*	*W*	*L*	V_0	V_1	V_2	*α*	F_1	F_2	*M*	*D*
Noda (1970)	√													
Kamphuis and Bowering (1970)	√							√						
Slingerland and Voight (1979)	√						√							√
Huber and Hager (1997)			√					√		√				√
Fritz (2002)	√			√										
Walder et al. (2003)		√						√						
Panizzo et al. (2005b)	√	√	√						√	√				
Di Risio (2005)	√			√										
Zweifel et al. (2006)	√			√									√	
Heller (2007)	√			√						√			√	
Ataie-Ashtiani and Nik-Khah (2008)	√	√					√				√			
Mohammed and Fritz (2012)	√		√	√	√	√								
Huang et al. (2014)	√			√							√	√		