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ESTIMATION OF THE WATER WAVES GENERATED BY THE LANDSLIDE IN THE GRIJALVA RIVER, MEXICO, 2007

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ABSTRACT

Large-scale water waves generated by landslides are one of the most dangerous events in reservoirs. Although the probability of occurrence is low, the consequences can be catastrophic as historical events have shown. The process of generation of the water waves is very complex, and has been studied with the aid of analytical, computational and physical models; empirical equations to estimate the characteristics of the water waves have been obtained depending on the parameters of the landslide. The paper presents a set of equations derived from physical models and real cases studies. The range of parameters and the hypothesis made in the experiments are discussed. Some of those equations are used to estimate the magnitude of the water waves generated as a result of a landslide of 50 Mm^3 in the Grijalva River, Chiapas, Mexico, occurred in November 2007. The results are compared with recorded data. The expressions that reproduce better that particular event are brought out and discussed.

KEY WORDS: *water waves, landslide, Grijalva*

INTRODUCTION

Water waves formed in coastal regions, a lake or reservoir due to impact of an earth or rock landslide, an avalanche, the fall of a glacier, or even the fall of a meteorite can be catastrophic. One of the most relevant and well documented of these events was in Vajont Reservoir in 1963. The wave generated by a landslide overtopped the dam and destroyed Longarone town downstream; nearly two thousand people were killed by the water wave (SCHNITTER, 1964).

If a chronological point of view is chosen, there are three characteristics stages in landslide waves. The first is the generation as a consequence of the impact of the landslide on the water body; the second phase is the propagations, dissipation and dispersion of the waves as they travel through the water body. The last stage corresponds to the interaction of the waves with the hillsides around the water body and with the dam or other infrastructure around; this last stage includes the wave reflection and run-up.

The most complex part of the phenomena is that related to the wave generation. This is because there is an interaction of the solid material entering the water body; this combination of a water displacement, flow resistance, disintegration of the landslide, etc., makes

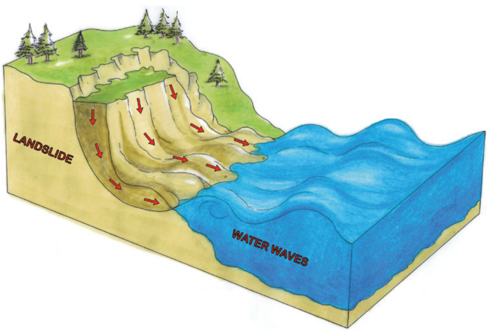

Fig. 1 - Water waves generation by landslide

it almost impossible to consider a general solution because there are a lot of variables involved (Fig. 1). This is why most of the cases are studied experimentally although the mathematical models have improved considerably in recent years. In addition, several studies have been developed in laboratory flumes or tanks in order to control the variables and be able to measure and observe the wave development, and compare predictions against observed historical events.

In the following, empirical expressions reported in the literature, mostly experimentally obtained, are presented and discussed. Some of them are applied for the prediction of the characteristics of the water waves generated after the Grijalva Landslide that occurred in November, 2007. The computed values are compared to the documented observations of the event.

EXPERIMENTAL STUDIES

There are several experimental studies related to impulse waves. Most of them were developed for flumes, where it is possible to control the relevant variables of the slide as its velocity, the angle of the slide, its density, etc.

One of the applicable results of the experimental studies are expressions for the maximum wave amplitude, a_M, or the total wave height, H_M, at the zone just in front of the landslide; additionally, there are some expressions for these variables as they travel from the above point, *a(x)* and *H(x)*. These expressions are function of the physical characteristics of the slide and of the body of water where the landslide impacts.

Di Risio *et alii* (2011) summarized the subject. Here we discuss the most relevant results that can be applied to our case. The first experiments reported went back to the XIX Century (Russell, 1838 & 1845). Solitary waves generated by the vertical falling box were studied. (Wiegel, 1955) was the first to study the waves generated by the impact of solid boxes sliding down inclines.

Cruickshank (1969) found that the shape of the box, the slide impact angle, and the vertical distance from the centroid of the mass sliding to the bottom of the flume are meaningless in the wave formation. He found that the relevant variables are the water volume displaced and the time the slide is moving in the water.

Noda (1970) classified the water waves as a function of the slide Froude number and the relative height of the slide. The first that reported experiments with moving sand bags were (Davidson & McCartney, 1975).

The Laboratory of Hydraulics, Hydrology and Glaciology of Zurich (VAW-ETH), (Huber, 1980 & 1982) reproduced the deformation and the porosity of the slide material using a granular mass. (Fritz *et alii*, 2003 & 2004; Zweifel, 2004; Zweifel *et alii*, 2006; Heller, 2007; Heller *et alii*, 2009; Heller & Hager, 2010) also worked in that laboratory. According to what we call the Swiss School the wave formation depends of the landslide velocity, V_s, the bulk slide volume, Vol_s, the slide thickness, *s*, the landslide width b, the landslide density, ρ_s, the porosity, *n*, the slide impact angle, α, and the water depth, *h*. On 2D experiments, the wave propagation is in the *x* direction and in 3D models the angle, γ, for the point where the wave is studied is also required.

2D EXPRESSIONS

Most of the already cited experiments were developed in flumes, so the characteristics of the water waves are just of a 2D wave and its one-directional movement in front of the landslide.

In order to reduce the number of variables, dimensional analysis is used. For (Kamphuis & Bowering, 1970) the relative wave height, *H(x)/h* (where *h* is the water depth); the dimensionless landslide volume per unit with, $Vol^*=Vol/(bh^2)$ (where *b* is the landslide width); the impact Froude number, $F=V_s/\sqrt{gh}$ (where V_s is the landslide velocity and *g* is the acceleration due to gravity); and the relative propagation distance, $X=x/h$ as is shown in the following equation:

$$\frac{H(x)}{h} = F^{0.7}(0.31 + 0.2\log(\mathrm{Vol}^*)) + +0.35\exp^{-0.08\,X} \quad (1)$$

As shown in equation 1, according to these authors, the waves decay exponentially.

Huber & Hager (1997) using (Huber, 1980) data formulated the next equation in which the impact angle and the specific gravity $G=\rho_s/\rho_w$ are considered:

$$\frac{H(x)}{h} = 0.88\left(\frac{G}{X}\right)^{0.25}\sqrt{\mathrm{Vol}^*}\sin\alpha \quad (2)$$

where ρ_s is the landslide bulk density and ρ_w is the water density.

Walder *et alii* (2003) worked on underwater landslides; they added the dimensionless underwater travel time, T_s:

$$\frac{a_M}{h} = 1.32\left(\frac{T_s}{\mathrm{Vol}^*}\right)^{-0.68} \quad (3)$$

T_s is a function of the dimensionless landslide length $L=l/h$.

$$T_s = 4.5L^{0.5} \quad (4)$$

This last Equation has been criticized because it does not involve the kinetic energy of the slide.

Very recently, FRITZ (2002), worked on a wave flume at the VAW-ETH laboratory generating waves with a pneumatic landslide generator. He measured the velocity field using Particle Image Velocity (PIV). His results are formalized in (FRITZ *et alii,* 2004) resulting in the next equation:

$$\frac{a_M}{h} = 0.25F^{1.4}S^{0.8} \quad (5)$$

where $S=s/h$ is dimensionless landslide thickness.

DI RISIO (2005) extended the works of KAMPHUIS & BOWERING (1970) for vertical falling box or landslide with α=90°, and proposed the following equations:

$$\frac{H_M}{h} = 0.897\, S^{0.642}F^{0.531}X^{-0.273} \quad (6)$$

$$\frac{a_M}{h} = 0.472\, S^{0.832}F^{0.398}X^{-0.215} \quad (7)$$

ZWEIFEL *et alii* (2006) using FRITZ (2002) results formulated the near field equation:

$$\frac{a_M}{h} = 0.33FS^{0.5}\mathrm{Vol}^{*0.25}G^{0.25} \quad (8)$$

For the far field, they formulated the next equation useful to obtain a as a function of the distance, *x:*

$$\frac{a(x)}{h} = 2S^{0.5}\tanh\left(0.25F^{1.5}\mathrm{Vol}^{*0.5}X^{-0.5}\right) \quad (9)$$

ATAIE-ASHTIANI & NIK-KHAH (2008) showed again that the landslide shape does not strongly affect the wave height. Instead, they included the new dimensionless landslide length, $L^*=l/s$:

$$\frac{a(x)}{h} = \left(0.398 + 0.076\mathrm{Vol}^{*1.27}F^{2.54}\right) \cdot \left(\frac{\mathrm{Vol}^*}{T_s^*}\right)^{0.26} L^{*-0.125}X^{-0.48} \quad (10)$$

Dimensionless underwater travel time, T_s*, is computed with the empirical equation of PANIZZO *et alii* (2005):

$$T_s^* = 0.43(A)^{-0.27}F^{-0.66}(\sin\alpha)^{-1.32} \quad (11)$$

where $A=bs/h^2$ is dimensionless landslide front area.

HELLER (2007) continued FRITZ, (2002) and ZWEIFEL (2004) experiments and proposed to include the impulse product parameter:

$$P = FS^{1/2}M^{1/4}(\cos(0.86\alpha))^{1/2} \quad (12)$$

with experimental ranges: 0.17≤P≤8.13

This parameter is used in the following set of equations for near field (if $X<5.5P^{(1/2)}$)

$$\frac{a_M}{h} = 0.44P^{4/5} \quad (13)$$

$$\frac{H_M}{h} = 0.56P^{4/5} \quad (14)$$

For far field (if $X\geq 5.5P^{(1/2)}$)

$$\frac{a(x)}{h} = 0.6\left(PX^{-1/3}\right)^{4/5} \quad (15)$$

$$\frac{H(x)}{h} = 0.75\left(PX^{-1/3}\right)^{4/5} \quad (16)$$

3D EXPRESSIONS

The first experiments in a tank were reported by JOHNSON & BERNAL (1949), however SINGERLAND & VOIGHT (1979) summarized their experimental results in the following equation:

$$\log\left(\frac{a_M}{h}\right) = -1.25 + 0.71\log\left(\frac{\mathrm{Vol}^*\, GF^2}{2h^3}\right) \quad (17)$$

PANIZZO *et alii* (2005), using a rigid block in a rectangular tank, measured the 3D wave propagation and proposed the next equation:

$$\frac{H(x)}{h} = 0.07\left(\frac{T_s^*}{A}\right)^{-0.45} X^{-0.44} \cdot (\sin\alpha)^{-0.88}\exp^{0.6\cos\gamma} \quad (18)$$

HUBER & HAGER (1997) using HUBER (1980) experiments proposed the next 3D expression:

$$\frac{H(x)}{h} = 1.76X^{-0.6}\mathrm{Vol}^{*0.5}G^{0.25}\sin\alpha\cos^2(0.67\gamma) \quad (19)$$

Finally, HELLER *et alii* (2009) using the scale model experiments of Lituya Bay and the Lucerne Lake, and their 2D flume experiments, proposed the next equation valid for far field ($X\geq 5.5P^{(1/2)}$):

$$\frac{H(x)}{h} = 0.75P^{0.8}\cos^2(0.67\gamma)X^{-0.67} \quad (20)$$

The all dimensionless quantity ranges of the experimental parameters are reported below in Tab. 1.

CASE STUDY: SAN JUAN GRIJALVA LANDSLIDE

The Grijalva Reservoir is located at the south-east of Mexico; the watershed has about 60,000 km^2, mainly at the State of Chiapas, and ends in the Gulf of Mexico (Fig. 2). At the upper part of the basin, the average year precipitation varies between 1,200 and 1,700 mm meanwhile at the lower part is a little above 4,000 mm, one of the biggest in Mexico. These conditions are mainly due to the presence of what meteorologist call tropical systems. The average volume at the mouth of the Grijalva River is 36,000 Mm^3.

There are four dams in cascade used mainly for hydroelectric generation and flood control; these are, coming from upstream, Angostura, Chicoasen, Malpaso and Peñitas.

The San Juan de Grijalva landslide happened in the Peñitas reservoir, in a huge river meander. Peñitas dam is about 14 km downstream the landslide site and Malpaso Dam is over 60 km upstream. The basin in the region is relatively narrow (from 200 to 400 m wide). About 100 m upstream the San Juan Grijalva Village was located.

Eq.	*Landslide model*	*F*	Vol *	G	*S*	*α* (°)
1	2D solid	0.9-3.1	0.04-0.79	2.7	0.13-0.88	30-90
2	2D granular	0.5-3.7	0.03-2.6	1.33	---	28-60
3	2D solid	1-4.1	0.14-3.24	2.9	0.24-1	11.2, 15, 19.5
5	2D granular	1.1-4.7	0.07-6.2	1.62	0.07-0.6	45
6,7	2D solid	0.3-2.6	0.1-4.2	1.36	0.22-2.5	90
8,9	2D granular	1.1-4.9	0.04-1.4	0.95-2.64	0.08-1.13	45
10	2D solid	---	---	1.8-2.0	0.1-0.4	15-60
13,14, 15,16	2D granular	0.9-6.9	0.05-3.0	0.59-1.72	0.09-1.64	30-90
17	3D granular	---	---	2.7	0.4-0.8	--
18	3D solid	1.0-2.2	---	2.2	0.11-0.45	16-36
19,20	3D granular	0.9-6.9	0.05-3.0	0.59-1.72	0.09-1.64	30-90

Tab. 1 - Experimental range of empirical formulations

	ALCÁNTARA & DOMÍNGUEZ, 2008	ARVIZU *et al*, 2008	HERNÁNDEZ *et al*, 2010	HINOJOSA *et al*, 2011
Evacuated	3500	---	3606	---
Dead	24	20	16	25
Vol [Mm^3]	55	55	50	47.4*
α [°]	10	8 a 10	5 a 20	15.64*
l [m]	1200*	---	Max 1570	1300
b [m]	610*	---	Max 1170	---
s [m]	70*	---	80	75
H(x) [m]	20	50*	> 15	50*

Tab. 2 - San Juan Grijalva landslide data

LANDSLIDE CHARACTERISTICS

According to (DOMÍNGUEZ, 2008), the main controlling factors of the San Juan Grijalva Landslide were a combination of:

- Intense precipitation
- Structural geology (faults and fractures)
- Water level changes and suction regime in the rock layers and rock dipping
- Mechanical properties of materials, expressly of lutites, which lowered their resistance when saturated
- Spatial distribution and stratigraphic character of the rock masses
- Local topography, although the slope gradient before the landslide was slightly higher than 10 degrees
- River bank erosion
- Deforestation

Additionally, there was a M4.5 earthquake in the region 5 days before.

More than 1,500 mm of rainfall were recorded during October, and 1,160 mm in just nine days very near the landslide date. The soil at the region was completely saturated, limiting the infiltration, (HINOJOSA, 2011). The spillway of Peñitas Dam was operating in order to control the big flood that was occurring at the basin. The water level at the reservoir was above the maximum operation level.

THE EVENT

At 20:32 hrs of Sunday November 4th, 2007, the Cerro La Pera, slid towards the Grijalva river. Field

Fig. 2 - Location of the Landslide

observation and the stratigraphic and geological setting of the region near San Juan Grijalva allows the conclusion, according to (ALCÁNTARA, 2008 & USGS, 2004) that there was a translational mass movement and the slide surface took place on a lutite layer.

The size of the landslide was huge (more than 50 Mm^3) and the river was completely closed. Moreover, part of the slide material rose on the opposite river margin. The impact of the landslide generated water waves that traveled upstream and downstream the landslide site. Fortunately, the reservoir widens considerably before the Peñitas Dam, so the waves damped out almost completely. No damage was reported at the dam infrastructure. On the contrary, as the water waves travelled upstream, San Juan Grijalva Town was razed to the ground. The small village was located 100 m upstream the face of the landslide and, at the same river margin, so γ=90° as can be seen in Fig. 3. The waves were dissipated as they traveled upstream, and no more damage was reported. No waves were reported at the town Raudales de Malpaso, just downstream of Malpaso´s Dam.

The data in Table 2 was taken from (DOMÍNGUEZ, 2008; ALCÁNTARA & DOMÍNGUEZ, 2008; ARVIZU *et alii,* 2008; HERNÁNDEZ *et alii*, 2010, and HINOJOSA *et alii*, 2011). As it is common for these kind of events, there are differences in the data.

Other characteristics of the landslide are reported in Table 3. Note that the water depth in the reservoir at the site of the landslide is relatively small considering the total volume of the slide. For that reason, the landslide closed completely the river

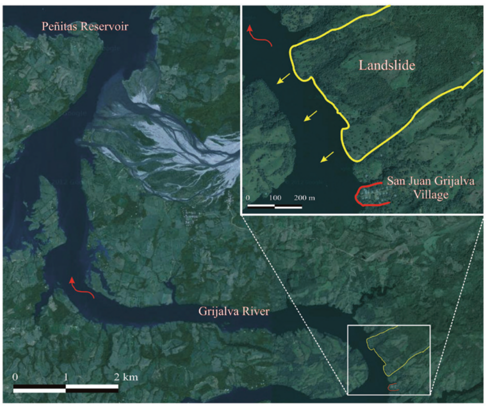

Fig. 3 - Landslide and San Juan Grijalva Village, (Extracted from Google Earth)

RESULTS

In Table 4, the dimensionless parameter computed using the most reliable data is reported

The computed wave characteristics are reported in Table 5, for the different equations that can be applied in this case. (ARVIZU *et alii*, 2008; HINOJOSA *et alii*, 2011) reported that the water wave at San Juan Village was *H(x)*=50 m. The splash region of the landslide is so near the town, X<5.5P$^{(1/2)}$, that the results for H_M could also be considered valid.

DISCUSSION

The water wave height and total wave height obtained with Eqs. (1) (KAMPHUIS & BOWERING, 1972), (2) (HUBER & HAGER, 1997), (6) (DI RISIO, 2005), (14) (HELLER, 2007), for 2D models overestimate the values. The differences with the estimated waves characteristics reported from in situ observations are reported in the last column of Table 5.

Variable	Value	Comments
h [m]	52	Measured form (HERNÁNDEZ *et al*, 2010) report.
x [m]	100	
γ [°]	90	
ρ_s [kg/m^3]	1725	(HINOJOSA *et al*, 2011)
n [%]	25	
V_s [m/s]	35	Estimated according to the analysis of (HINOJOSA *et al*, 2011)

Tab. 3 - Landslide characteristics

Landslide	F	Vol *	G	S	X	α [°]	γ[°]
3D granular	1.55	28.7	1.725	1.3	1.9	14	90

Tab. 4 - Dimensionless parameters of San Juan Grijalva Landslide

Eq.	H_M [m]	a_M [m]	$H(x)$ [m]	$a(x)$ [m]	*%Differences* $H(x)$
1	---	---	58	---	16
2	---	---	64	---	29
3	---	99	---	---	---
5	---	30	---	---	---
6	60	---	---	---	19
7	---	39	---	---	---
8	---	71	---	---	---
9	---	---	---	102	---
10	---	1118	---	---	---
13	---	80	---	---	---
14	100	---	---	---	100
17	---	249	---	---	---
18	---	---	32	---	-36
19	---	---	25	---	-50
20	---	---	41	---	-57

Tab. 5 - Water wave characteristic

On the contrary, the 3D expressions, Eqs. (18) (Panizzo *et alii*, 2005), (19) (Huber & Hager, 1997) and (20) (Heller *et alii*, 2009); underestimate the wave height.

These differences can be explained because in the 2D experiments, the energy of the block is more efficient transmitted to the water waves been generated; besides the propagation is just in the same direction of the movement (γ=0°). Besides, in 3D, the water waves disperse of the waves as they travel through the reservoir.

Also, it can be noted that the equations for granular landslides give lower wave heights tan those of block slides because the soil porosity permits to absorb part of the energy of the slide dynamics, mainly after the impact of the slide with the reservoir.

We believe that the block dynamics as it is moving in the reservoir has a strong influence on the water waves' characteristics. The specific gravity of the landslide is also important in the buoyancy force that is in opposite direction to the movement of the slide. The dimensionless landslide volume per unit with is the relationship of the volume of the block compared to the water depth. In the case here discussed, $Vol >> bh^2$; besides, the size of the block is also bigger than the water depth ($s>h$ $S>1$). The landslide ended its movement with just a part underwater and closing completely the river. This situation is not considered in most of the equations.

CONCLUSIONS

Empirical equations were used in order to estimate the water wave height at San Juan Grijalva Town, after the landslide of November 2007.

The 2D models overestimate the water wave height (from 16% to 100%) if the values of 50 m reported in the literature are considered. The location of San Juan Grijalva Town and the direction of the landslide suggest that a 3D description could be more adequate. Nevertheless, the computed values are under the 50 m height (from -36% to -57%). The event characteristics of the San Juan landslide are such than just the landslide Froude number is in the rank of the experiments reported in the literature, but the dimensionless landslide volume per unit width and landslide thickness are much bigger of the experimental parameters for most of the equations. Furthermore, experiments where the landslide ended partially submerged are required (as it is the case in the Grijalva Lanslide).

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