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EXPERIMENTAL STUDIES ON 3D IMPULSE WAVES GENERATED BY RAPID LANDSLIDES AND DEBRIS FLOWS

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ABSTRACT

The input of material in a water body at high velocity, like a landslide or a debris flow, can induce a big, abnormal wave, known as impulse wave or landslide tsunami wave. Once the wave is triggered, the effects on the shorelines are devastating and moreover unlikely predicted. Disastrous past events have been extensively analysed but remain too scarce to properly describe the process. Experiments of impulse waves have been carried out by various authors. The present work was planned to fill the lack of experimental data on the effect of granular material falling in a water basin, exploring new ranges of parameters governing this process.

It is introduced a new experimental set up installed in the fluvial-morphodynamic laboratory of the GITS team in the Technical University of Catalonia. The experimental device consists of a wheeled box sliding on a steeply sloped flume and releasing granular material, which ends up in a basin. The system allows reaching a relatively high velocity of the granular mass for a correct simulation of the process's behaviour.

A system has been defined in order to be able to measure the velocity of the granular material and its depth, as well as the propagation of the waves, with high-speed cameras and a laser grid system. The dynamic forces of the granular mass' impact on different surfaces is also measured and related to the studied phenomenon.

Several experiments' runs have been carried out. First results are here presented and analysed.

Key words: *impulse waves, debris flow, landslide*

INTRODUCTION

An impulse wave is created when a sufficient quantity of material, having a high velocity, enters a reservoir, a natural lake, a fjord or the sea. The momentum of the sliding material is transferred to a mass of water turning into a giant wave able to travel large distances.

That particular phenomenon, known also as landslide tsunami wave, can be highly destructive and unlikely predicted. Block mass, granular mass as well as volcanic lava can trigger such phenomenon. The present study focuses on granular mass sliding in a water body.

That phenomenon can take place in mountainous zones where slopes instability is more frequent. A landslide or a debris flow can be triggered by means of various behaviours as the increase of water pore pressure in the soil due to heavy rainfall or snow melting, earthquakes and defrosting of alpine permafrost in between others (Coussot & Meunier, 1996; Hungr *et alii*, 2001; Iverson *et alii*, 1997). When such sliding mass with a relative high velocity hit a water body, a set of giant waves is generated and propagates for a long distance. Initially that wave can produce a very large run-up of hundreds of meters destroying the shoreline or easily overtop dams (Panizzo *et alii*, 2005).

Although having a high destructive potential, debris flows or landslides seem to produce a tsunami wave that rapidly decays if compared with earthquake

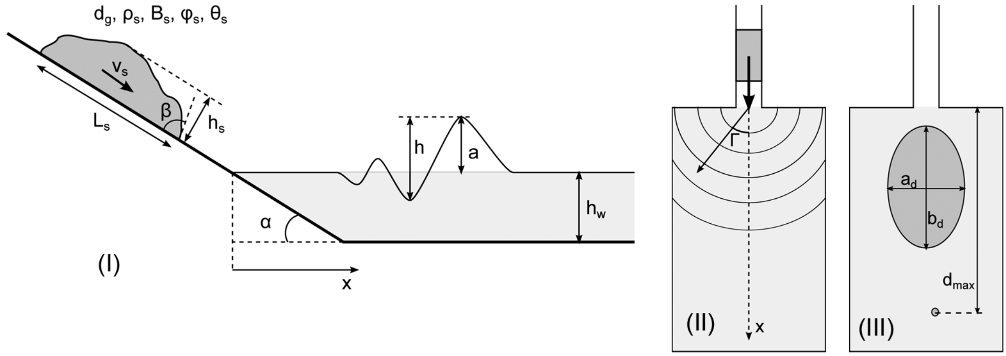

Fig. 1 - Sketch of the phenomenon and the related governing parameters: (I) lateral view; (II) aerial view of the channel with the coordinates system; (III) aerial view of the schematic final deposit of material

tsunamis (Heller & Hager, 2010). It suggests the different scale of the processes and the forces involved: crustal blocks that move during large earthquakes are incomparably larger than any landslide.

Disastrous past events are testimonials of impulse wave's power. Some catastrophes are well reported by different authors: Ariake Bay, Japan 1792 (Miyamoto, 2010); Lituya Bay, Alaska 1958 (Fritz *et alii*, 2001); Vajont Dam, Italy 1963 (Datei, 1968); Lake Yanahuin, Perú 1971 (Slingerland & Voight, 1979); Stromboli Island, Italy (various events, Maramai *et alii*, 2005; Tinti *et alii*, 2005; Bellotti, *et alii*, 2009).

Experimental studies have been carried out with a rigid body or a sliding granular material plunging in a straight channel (two-dimensional, 2D) or in a water basin (three-dimensional, 3D).

Works on 2D channel are, among others: Russell (1837), Noda (1970), Kamphuis & Bowering (1972), Huber (1980), Fritz (2002), Zweifel (2006) and Heller *et alii* (2007).

Works on 3D basin are, among others: Huber (1980), Panizzo *et alii* (2005) and Di Risio (2009).

In particular, these last two works are concerning a rigid body entering a water basin.

In the present studies a new laboratory facility described hereafter is set up to explore new range of variables of the presented phenomena for a granular sliding mass entering in a water basin. A new measuring system is settled up too. The preliminary experimental results are presented and discussed.

PARAMETRIZATION OF THE PHENOMENON

The complexity of the phenomenon is highlighted by the considerable number of parameters involved, and not always easy to control (Fig. 1). The parameters are listed in Tab. 1.

Parameter	Dimension	Description
v_s	$[LT^{-1}]$	velocity of the LS
h_s	[L]	thickness of the LS
B_s	[L]	width of the LS
L_s	[L]	length of the LS
φ_s	[-]	internal friction angle of LS
θ_s	[-]	porosity of LS
d_g	[L]	grain size of LS
ρ_s	$[ML^{-3}]$	density of the LS
α	[-]	impact angle
β	[-]	angle front-slope
ρ_w	$[ML^{-3}]$	density of water
h_w	[L]	Initial water depth in basin
a	[L]	wave ampltude
h	[L]	wave height
g	$[LT^{-2}]$	gravity
a_d	[L]	minor axis of the FD
b_d	[L]	major axis of the FD
d_{max}	[L]	Dist. of the FD's farthest grain
x	[L]	distance from the impact
Γ	[-]	wave direction

Tab. 1 - List and description of governing parameters. LS: landslide; FD: Final Deposit

Some considerations and simplifications are initially introduced for the presented study:

- only one type of bulk material is considered;
- the sliding mass hit the water body perpendicular to the slope ($\beta = 90°$);
- only constant sliding slope angle, width and length of sliding mass are considered;
- only the principal direction ($\Gamma = 0°$) is considered.

Nevertheless almost every parameters can be modified, according to the configuration of the experiment.

Given the previous hypothesis, the wave amplitude *a*, as well as the wave height *h*, is a function of a reduced number of variables as below

$$a = f\left(v_s, h_s, h_w, a_d, b_d, d_{\max}, g, x,\right) \quad (1)$$

$$h = f\left(v_s, h_s, h_w, a_d, b_d, d_{\max}, g, x,\right) \quad (2)$$

$$a_M = f\left(v_s, h_s, h_w, a_d, b_d, d_{\max}, g\right) \quad (3)$$

$$h_M = f\left(v_s, h_s, h_w, a_d, b_d, d_{\max}, g\right) \quad (4)$$

where the subscript *M* means the maximum value of the wave's amplitude and height, which are registered near the impact.

With the objective to properly and synthetically describe the phenomenon in act, new parameters are defined (dimensions in square bracket):

- The momentum flux of the sediment,

$$\Phi_s = v_s^2 h_s, \left[L^3 T^{-2}\right] \quad (5)$$

- The initial water pressure,

$$P_w = h_w^2 / 2, \left[L^2\right] \quad (6)$$

These magnitudes can be related in a new dimensionless parameter:

$$\Psi = \Phi_s / P_w = 2 v_s^2 h_s / g\, h_w^2 \quad (7)$$

Other interesting parameters are the ones related to the final deposit that can be synthesized as the ellipse's area $A_d = \pi a_d b_d$ which is a measure of the basal friction the deposit has experienced.

EXPERIMENTAL SET-UP

A new experimental device has been settled in the laboratory of Hydraulic Engineering of the Technical University of Catalonia in Barcelona. The facility was planned to study the effect of a granular slide plunging in a basin.

The set up consists in a steep flume with a variable

Fig. 2 - Frontal view of the box sliding on the flume; on the top of the kart, the piston that absorbs the hit

Fig. 3 - The slide is plunging in the basin after the doors opened. In this case the mass is 120 kg, reaching a velocity of around 5.5 m/s on a slope of 27.5º. The frame is taken from a video of a high velocity camera recording at 650 frames per second (f/s)

slope where a metallic wheeled box is sliding along rails with a low roughness. At the end of the channel, a high resistance piston suddenly stops the box forcing the opening of the door and thus the releasing of the granular material (see Fig. 2 and Fig. 3).

The material plunges into the basin and triggers a set of waves.

The main characteristics of the experimental device are: (1) maximum sliding length 6.20 m, (2) angle of impact up to 27.5º, (3) slide impact velocity up to 6 m/s, (4) sliding mass weight up to 150 kg, (5) initial basin's water depth from 0.2 to 0.6 m, (6) dimension of the basin 4.10x2.45 m.

Due to the reduced dimension of the basin in respect to the velocity of propagation of the produced waves, only the first wave can be measured: the followings are distorted by the reflection on boundaries.

In the laboratory, granular materials with different characteristics are available. At the moment the granular material used corresponds to selected white gravel with a mean grain diameter of 19.5 mm and a median diameter of 16.9 mm (see Fig. 3).

MEASUREMENTS

To run a complete experiment actually is necessary to repeat the same experiment twice at different environmental condition. The first experiment (named *type a*) is carried out with a high velocity camera (650 frames per second) focusing on the inlet of the basin with a powerful illumination (Fig. 3). A calibration grid is applied and the measurement of the geometry and velocity of the granular slide material is achieved.

The second experiment (named *type b*) is carried out to observe the propagation of the wave. Three high definition video cameras record the basin from different points of view, where different laser sheets project lines that mark the free surface. The water is previously filled with a small amount of kaolin that colours the fluid, reflecting the lasers (Fig. 4).

Using a calibration process and mathematical transformation's algorithm created *ad-hoc*, the metrical measurement with a high precision is achieved (Bregoli, 2008). The final deposit is also measured after each run once the basin is emptied.

The evaluation of the maximum wave's height and amplitude needs a particular caution. The formation of the wave is anticipated by a big splash in the zone of impact, making difficult the choice of the maximum wave's height. A description of that process is given in the Fig. 5, where it is possible to appreciate the evolution of the impulse wave. The water splash and the first formed wave have a completely different size, the first being much greater that the second. A similar situation is described in Fritz *et alii* (2004). For that reason, it is decided to differentiate between the measurement of the maximum wave's height and the initial splash.

RECENT ADVANCEMENTS ON DEBRIS-FLOW IMPACT

Recently a high-frequency-response load cell has been purchased in order to conduct a parallel research. The study consists on the evaluation of the effect of a debris flow hitting vertical structures. The intent is to analyse the efficiency of various countermeasure structures like walls and deflectors, and the stress experienced. The experiments have been run in the same configuration as the impulse wave generation. Therefore this research could be an opportunity to study the pressure that a granular sliding mass can produce in correspondence to the entrance into the basin. That pressure can be related to the produced wave to better understand the formation and behaviour of waves.

The load cell (sketch in Fig. 6 I) is able to meas-

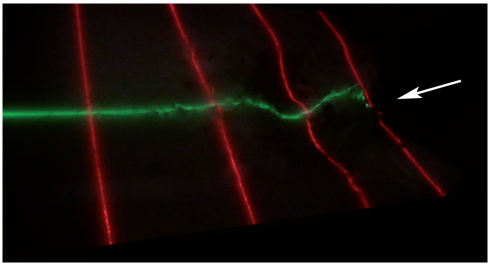

Fig. 4 - Laser grid reflecting over the water surface, filled by kaolin. The arrow represents the direction of the sliding mass entering in the basin. The material is already plunged in the water and the wave is forming. The green line shows the main direction of propagation

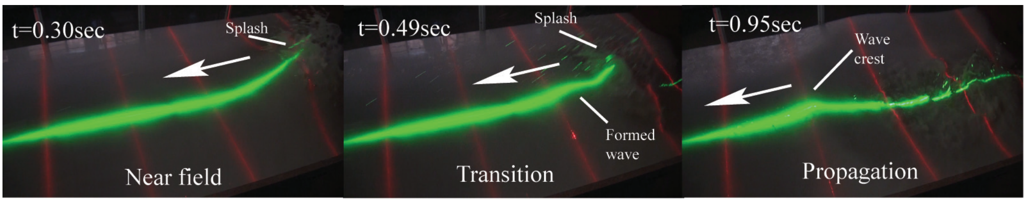

Fig. 5 - Photo sequences at 26.43 f/s of a forming wave triggered by a mass of 125 kg sliding along a slope of 27.80°. The arrows represent the main direction of wave's propagation which corresponds with the direction of the entering sliding mass. The basin's water depth is 0.2 m. The splash (near field), the formation of the wave (transition) and a defined wave crest travelling along the basin (propagation) are visible

Fig. 6 - Experiments on debris flow's impact on structure. (I) sketch of the load cell, able to measure forces and torques along the 3 directions; (II) lateral view of the planar plate structure (check-dam) with the integrated load cell; (III) view of the "comb" structure (filter-dam)

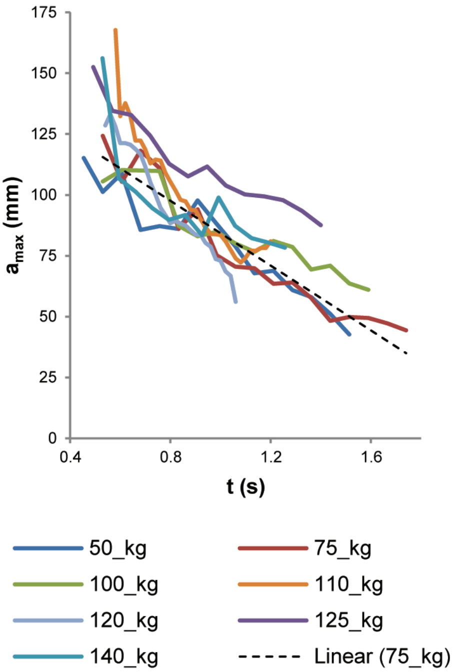

Fig. 7 - Decay of the wave crest over time. The legend shows the different runs, where the codes correspond to the mass of sliding material. The dotted line represents the linear regression of the 75 kg's run, $a_{max} = -66.56t + 150.76$, $R^2 = 0.915$

ure forces and torques along the three direction with a frequency of 1000 Hz. The structures used for this research are: a planar structure (that simulates a check-dam, Fig. 6 II), a "comb" structure (that simulated a filter-dam, Fig. 6 III), a deflector at different degrees and a system to study the vertical distribution of impact's forces of the granular slide. For the present study, only the planar structure is taken into account.

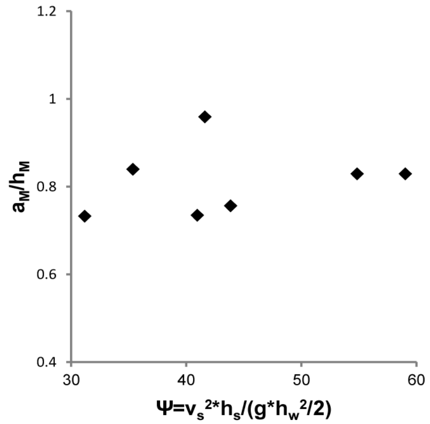

Fig. 8 - Relation between the ratio of maximum amplitude and maximum height of wave and the dimensionless parameter Ψ

RESULTS

14 runs, corresponding to 7 complete experiments have been carried out. The results presented, concern the principal direction ($\Gamma = 0°$), marked with the green laser sheet (see Fig. 5).

A plot of the evolution of the wave for the different runs is presented in Fig. 7, where it can be appreciated the decay of the waves over the time. The decay is similar for every run. The example of regression line for the run relative to a slide of 75 kg, shows a strong wave's decay of 66 mm/s, which corresponds to a reduction of around 50% in 1 second, respect to the initial wave amplitude.

In the Fig. 8 the relationship between the ratio of maximum amplitude and maximum height of wave and the dimensionless parameter Ψ is reported. In this case, it is difficult to recognize a pattern, due to the limited range of parameters.

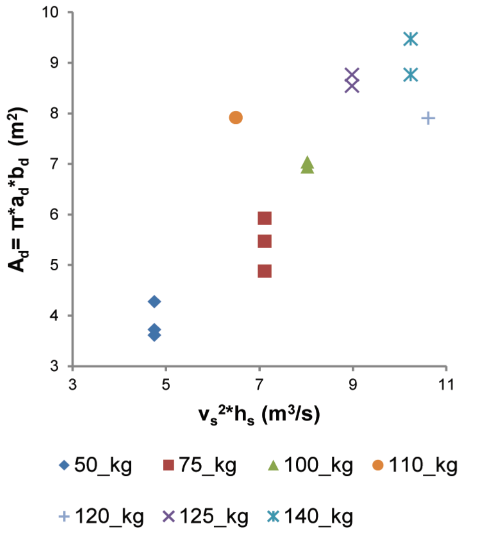

Fig. 9 - Relation between the basal friction experienced by the deposit and the momentum sediment flux

Data of the final deposit's geometry are recollected. The basal area of the final deposit is thus related to the momentum flux of the sediment, showing a comforting trend (Fig. 9).

Results of experiments on debris flow's impact are reported in Tab. 2. Here it can be observed that the weight increases with increasing impact forces (maximum and medium). Fixing the weight and varying the height of the slide, the maximum force of impact is proportional to the height (Fig. 10). The Relation of maximum force over the averaged force of impact and the Froude number of the slide is shown on Fig. 11.

DISCUSSION AND CONCLUDING REMARKS

An experimental device is set up to study the phenomenon of impulse wave. The facility generating high speed granular slides is able to perform the described behaviour correctly. The high velocity is necessary to create a high turbulence where high Reynolds number allows a certain comparison between laboratory and reality.

The limited number of experiment and the narrow range of variables such as vs are not always enough to define pattern of regression. The relationships shown in Fig. 8 should be a good way to relate consequence (wave height) and cause (the sliding mass opposing the water pressure), but it needs to be analysed in wider ranges of parameters.

	Mass (kg)	h_s (m)	v_s (m/s)	F_{max} (N)	F_m (N)
Diff. loads	50.00	0.12	6.00	2267.48	273.48
	75.00	0.18	5.87	4097.98	372.89
	100.00	0.26	6.60	4637.94	432.63
	110.00	0.29	6.00	5598.17	481.31
	125.00	0.27	6.05	5202.54	498.03
	140.00	0.28	5.94	5245.82	441.76
50 kg at different height	50.00	0.10	6.60	1499.33	289.46
	50.00	0.14	6.00	2593.66	303.25
	50.00	0.19	5.87	3707.39	303.89
	50.00	0.25	6.60	4245.99	303.28
75 kg at different height	75.00	0.09	5.94	2005.78	386.33
	75.00	0.18	5.78	2409.26	395.62
	75.00	0.21	5.78	3100.56	391.64
	75.00	0.26	6.00	4029.41	392.30

Tab. 2 - Results of experiments of impact over a planar structure at different loads and height of slide. Fmax is the maximum resultant force, Fm is the medium force, averaged in time till the stabilization

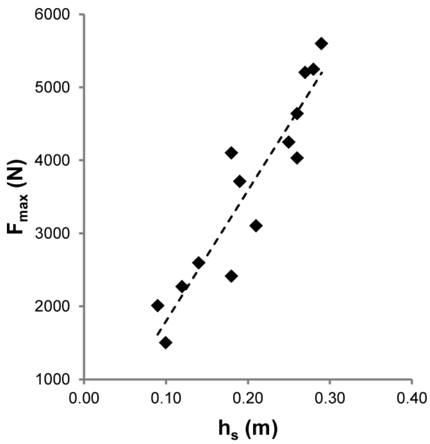

Fig. 10 - Relation between maximum force experienced by the planar plate and the height of the slide. Linear regression: $F_{max} = 17938h_s$, $R^2 = 0.867$

The experiments on slides impact over a planar plate give a clear idea on the relation between the characteristics of the slide and the triggered forces (Fig. 10). Moreover the relationship became stronger when only comparing the height of the sliding mass and the maximum force acting over the plate (Fig. 11). This remark gives to the height of the slide

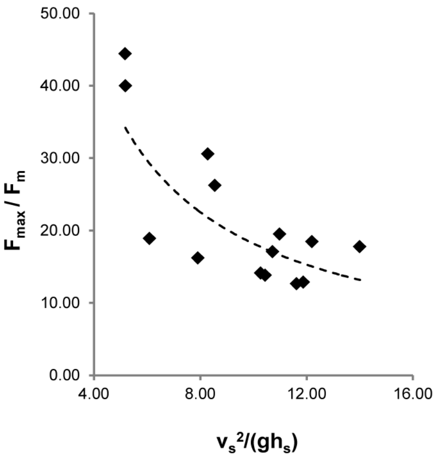

Fig. 11 - Dimensionless relationship between cause (velocity and depth of granular slide) and forces (maximum and average forces). The power regression is $y = 165.59x^{-0.96}$, $R^2 = 0.573$

an exceptional importance on the creation of impulsive waves, even if the comparison cannot be directly conducted because of the different behaviour in presence: hits against a vertical wall or a water basin differ significantly.

New experiments, exploring a wider range of variables, will be carried out to improve the variables correlations.

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