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ANALYSES AND DESIGN PROCEDURE OF A NEW PHYSICAL MODEL FOR DEBRIS FLOWS: RESULTS OF NUMERICAL SIMULATIONS BY MEANS OF LABORATORY TESTS

Nicola MORACI(*), Marilene PISANO(*), Maria Clorinda MANDAGLIO(*), Domenico GIOFFRE'(*),
Manuel PASTOR(**) , Giovanni LEONARDI(*) & Simonetta COLA(***)

(*) *Mediterranea University of Reggio Calabria - Dep. DICEAM - via Graziella Loc. Feo di Vito - 89060 Reggio Calabria, Italy. nicola.moraci@unirc.it*
(**)*ETS de Ingenieros de Caminos - Universidad Politécnica de Madrid - Ciudad Universitaria, s/n - 28040 Madrid, Spain*
(***)*University of Padua - Dep. ICEA - via Ognissanti, 39 - 35129 Padova, Italy*

EXTENDED ABSTRACT

In Italia diverse regioni presentano un elevato rischio idrogeologico connesso a fenomeni franosi di colata rapida. La Calabria e la Sicilia sono spesso interessate da tali eventi franosi, che producono ingenti danni alla popolazione, alle strutture e alle infrastrutture presenti nel territorio.

Una possibile strategia, volta alla mitigazione del rischio connesso a tali fenomeni, può essere perseguita con interventi di tipo strutturale quali opere di protezione passiva. Tali opere riducono il rischio connesso al fenomeno franoso arrestando o deviando il percorso della colata detritica.

Al fine di riprodurre le colate di detrito, uno degli obiettivi di ricerca del progetto PON01_01869, sviluppato dal gruppo geotecnico del Dipartimento DICEAM dell'Università "Mediterranea" di Reggio Calabria, è stato quello di realizzare un modello fisico di grandi dimensioni in grado di studiare il fenomeno della propagazione dei debris flow.

Il modello fisico è formato da quattro parti: i) una struttura principale costituita da uno scivolo in acciaio, con inclinazione variabile rispetto all'orizzontale, le cui pareti laterali in plexiglass consentono la videoripresa del flusso detritico; ii) un serbatoio a sezione rettangolare adibito al contenimento e al rilascio, con un meccanismo di tipo "dam-break", di miscele acqua-terreno; iii) una struttura per il sollevamento del serbatoio alle varie altezze di prova; iv) un sistema di misura, trasmissione, registrazione ed elaborazione dei dati di prova mediante l'impiego di sensori a ultrasuoni, trasduttori di pressione e videocamere ad alta definizione.

Per la progettazione del modello fisico sono state effettuate analisi numeriche, oggetto della presente memoria, allo scopo di valutare le dimensioni del modello necessarie a riprodurre le velocità di debris flow reali. Le analisi sono state realizzate utilizzando il codice di calcolo SPH (Pastor *et alii*, 2009) che lavora su un modello non lineare e accoppiato, permettendo la soluzione delle equazioni della dinamica del continuo in forma lagrangiana:

- il "modello matematico" basato sulle equazioni di conservazione della massa e della quantità di moto è semplificato effettuando un'integrazione in profondità (lungo l'asse verticale), considerato che i movimenti franosi studiati hanno profondità medie piccole rispetto alla loro lunghezza o larghezza;
- il "modello numerico" utilizza una tecnica di discretizzazione del campo di moto (metodo SPH, "smoothed particle hydrodynamics") attraverso un sufficiente numero di punti mobili, ciascuno rappresentativo di una particella fluida: il campo di moto è ottenuto interpolando in ogni punto del continuo i valori relativi ai singoli punti mobili attraverso l'uso di opportune funzioni di interpolazione.

Il modello, combinato alle adeguate relazioni costitutive, restituisce le velocità secondo il piano perpendicolare alla direzione di integrazione e la profondità del materiale in frana.

Per identificare la reologia delle miscele acqua-terreno sono state preliminarmente effettuate delle prove di laboratorio su una canaletta di piccole dimensioni. Per ricostituire le miscele rilasciate è stato utilizzato un volume solido costante (sabbia con ghiaia medio-fine) al quale sono stati aggiunti volumi d'acqua tali da ottenere diverse concentrazioni solide in volume. La scelta delle concentrazioni solide in volume è stata opportunamente operata prendendo in considerazione i valori tipici dei debris flow.

Attraverso una back-analysis numerica dei risultati delle prove di laboratorio, è stato ricavato il legame sforzi-deformazioni che meglio riproduce il comportamento reologico delle miscele indagate (legge reologica puramente attritiva). Inoltre, la calibrazione del parametro attritivo che governa tale legge reologica (coefficiente di attrito cinematico) ha consentito di definire una correlazione tra le concentrazioni solide in volume delle miscele e gli angoli di attrito ad esse corrispondenti.

Successivamente, utilizzando la reologia ricavata sperimentalmente, sono state effettuate le analisi numeriche per ricavare le dimensioni del modello fisico necessarie a riprodurre le velocità dei debris flow reali. In particolare, le analisi numeriche sono state condotte facendo variare i volumi (in termini di altezza di rilascio) e gli angoli di attrito delle miscele (considerando i casi estremi di solo fluido e materiale secco e le concentrazioni solide in volume tipiche dei debris flow); la lunghezza e l'inclinazione della canaletta rispetto all'orizzontale.

ABSTRACT

Debris flows are landslides that may involve large volumes of material and, due to their rapid propagation, they may be potentially dangerous for human lives and lifelines.

In this paper, numerical simulations carried out for designing an instrumented large-size physical model are shown. In particular, a parametric analysis has been performed in order to reproduce, with the flume tests, the debris flow velocities observed during real events.

Since the used computational code requires setting the specific rheological laws, several preliminary experimental tests have also been carried out, with the aim to find the rheological behaviour of the debris flow material.

Keywords: debris flow, flume test, rheological law, numerical analyses, design of physical model

INTRODUCTION

Debris flows are important landslides with a flow-like behaviour. During the flow the volume of landslide increases and the characteristics of the flow material may change, modifying the flow mobility. The high velocity that the flow mass can reach during propagation, due to the characteristics of both the moving material (i.e. debris) and the type of material in basal surface, allows that long distances can be rapidly covered. Moreover, the consequences of debris flow impact are pronounced when it occurs near infrastructures or other main lifelines, because it can produce the interruption of traffic or other activity or even the loss of human lives.

Debris flow materials are complex mixtures of sand, gravel, cobbles and boulders, often with varying proportions of silt and clay.

In addition to this, the different components of the debris flow materials can separate, with larger blocks moving upwards and onto the front. Moreover, spatial gradational sorting of debris flows, due to the development of inverse grading or coarse surge fronts, is common and may be important for the flow behaviour (e.g., Pierson, 1986).

Many classifications of flows exist in literature (Heim, 1932; Varnes, 1954, 1978; Cruden & Varnes, 1996; Pierson, 2005; Vallance, 2005; Keefer & Johnson, 1983; Hutchinson, 1968, 1988; Hungr *et alii*, 2001, etc.). According to Hungr *et alii* (2013), the term “debris flow” is used to describe very rapid to extremely rapid surging flows of saturated debris in a steep channel with strong entrapment of material and water from the flow path. It occurs periodically on established paths, usually gullies and first- or second order drainage channels. Thus, debris flow hazard is specific to a given path and deposition area (“debris fan”). This, with the periodicity of occurrence at the same location, influences the methodology of hazard studies and contrasts with related phenomena, such as debris avalanches, whose occurrence is not bound to an established path. Once debris begins to move in a steep channel, the bed is subjected to rapid undrained loading, often so sudden that it could be characterized as impact loading (Sassa, 1985). Under such conditions, even coarse material can liquefy, or at least suffer a significant increase in pore-pressure. The bed material will become dragged in a growing surge. As the surge moves downstream, erosion undermines the steep banks and further soil material, as well as organic debris, is added to the flow. The surges travel down the channel on slopes steeper than 10-20°. In many cases, it is found that the final mass is much larger to the initial, because of the entrainment along the path of propagation. Therefore, the magnitude of debris flows depends primarily on the characteristics of the channel and it can be estimated by empirical means (Hungr *et alii*, 2005).

It is important to notice that entrainment can be much larger in steep channels, as the bed can become unstable (Bagnold, 1966). The bed material can be massively mobilised and dragged into the flow (Hungr *et alii*, 2005). Debris surges spread out when the channel exits onto the surface of the debris (colluvial) fan, at typical slopes of 5° to 10°. The frontal boulder accumulation rapidly deposits in the form of levees or abandoned boulder fronts, while the finer and more dilute material continues further downslope.

In order to reduce the debris flow risk consequences of both hazard and vulnerability, structural and non-structural measures can be used. In both cases, it is important to predict the possible scenarios in order to propose effective protection works and safety measures.

Two general approaches are available for mitigating debris flow risk. The first approach (active approach) consists of decreasing the destabilizing forces that can trigger landslide; whereas the second approach (passive approach) is to carry out containment measures of the movement of the debris.

The most commonly used remedial measures to reduce the destabilizing forces are for example the modification of the slope geometry by excavation or toe fill and the drainage of surface and ground water. In particular, drainage is the most widely used method for slope stabilization. These remedial measures are excellent site-specific management tools for landslides if correctly designed and constructed, for example with regard to proper design of the filtering transitions (Moraci *et alii*, 2012a, b, c; Moraci *et alii*, 2014a; Moraci *et alii*, 2014b; Cazzuffi *et alii*, 2014; Moraci *et alii*, 2015).

An alternative landslide risk-mitigating strategy of engineering solutions is to control the movement of landslide debris so as to reduce the spatial impact of landslides on elements sensitive at risk. Mitigation measures consist in the passive structural barriers usually made with earth reinforced embankment or dams located to intercept or divert the flow along the channel.

The knowledge of the physical, kinematic, geometric and rheological properties of debris flow (e.g., concentration of solid material, the evolutionary characteristics of viscous water / soil mass movement, speed profile, thickness) are required to design protection embankments. The state of knowledge for the design passive structures for the protection from rapid debris flows, especially for the design of earth reinforced embankments, is not yet supported by a comprehensive scientific literature.

Numerical models contribute significantly to describe the consequences of large mass movements. Several numerical models have been developed for simulating landslide propagation and runout (e.g. Savage & Hutter 1989; Gray *et alii*, 1999; Chen & Lee, 2000; Denlinger & Iverson, 2004; McDougall & Hungr, 2004; Quecedo *et alii*, 2004; Pastor *et alii*, 2009; Pirulli & Pastor, 2012; Borrelli *et alii*, 2012). Whatever code is used, the choice of the correct rheology and of the rheological parameter values is fundamental. Due to the large dimensions of real phenomena, back analyses of debris flows already occurred are the only way to obtain data for runout prediction analyses (e.g. Hungr & Evans, 1996). Nevertheless, a lack of knowledge in geometrical and geomechanical information may lead, in the back analyses, to wrong interpretations of the mechanics of the event and inaccurate calibration of numerical models.

In this context, data from measurements made on site or experimental channel tests are important both in terms of the theoretical aspects of the problem (determination of the rheological behaviour, calibration of numerical models) and in terms of practical aspects (passive barrier or prevention of phenomenon, definition of alarm systems, etc.). The main variables that can be measured or calculated are: physical and mechanical properties, height, velocity, image or video and mobility of debris flow (Suwa, 1989; Lahusen, 1996; Arattano *et alii*, 1997; Genevois *et alii*, 2000a, b; Berti *et alii*, 2000; Aliperta *et alii*, 2012). Many studies aim at the analysis of trigger phenomena of landslides (Musso & Olivares, 2003; Olivares & Picarelli, 2003; Cascini & Sorbino 2003), at the analysis of the fluidization of landslide (Musso *et alii*, 2004) and at the analysis of propagation (runout, runup) of debris flows (Iverson, 1997; Prestininzi & Romeo, 2000; Mandaglio *et alii*, 2015).

The paper focuses on numerical simulations carried out for the design of a large-size physical model in order to study the debris flow propagation.

Specifically, the research aims to reproduce, by means of the large-size physical model, the debris flow velocities observed during real events.

In order to calculate the debris flow velocities by means of the numerical code, it is necessary to know the rheological law of mixtures which will be used in the research. The rheological law has been found carrying out several experimental tests.

Fixed the rheological law, by means of the parametric numerical analysis it has been possible to design the geometric characteristics of the physical model, necessary to reproduce the typical velocities of debris flows.

MODEL USED TO SIMULATE THE PROPAGATION (DEPTH-INTEGRATED COUPLED SPH MODEL)

The distinctive features of this flow-like landslide are strictly related to the mechanical and rheological properties of the involved materials, which are responsible for their long travel distances (up to tens of kilometres) and the high velocities (in the order of meters/second) they may attain. The prediction of both run out distances and velocity through mathematical modelling of the propagation stage can notably reduce losses inferred by these phenomena, as it provides a mean for defining the hazardous areas, estimating the intensity of the hazard (which serves as input in risk studies), and for working out the information for the identification and design of appropriate protective measures. In the past decades, modelling of the propagation stage has been largely carried out in the framework of the continuum mechanics, and a number of new and sophisticated numerical models have been developed.

Among the numerical codes developed in the last twenty years to predict the propagation of flow-like landslide in the framework of the continuum and discrete element mechanics, the depth-integrated SPH method proposed by Pastor *et alii* (2009) is particularly suitable for this kind of analysis.

The mathematical model of SPH method proposed by Pastor *et alii* (2009) is based on v-pw Zienkiewicz–Biot model, consisting of:

(i) The balance of mass, combined with the balance of linear momentum of the pore fluid, which in the case of saturated soils reads

$$-div\left(k_w \cdot grad\ p_w\right) + div\,v_s + \frac{1}{Q} \cdot \frac{D^{(s)} p_w}{Dt} = 0 \qquad (1)$$

where k_w is the permeability coefficient, v_s is the velocity of soil skeleton, $D^{(s)}$ refers to a material derivative following the soil particles and the equivalent volumetric stiffness Q is given in terms of soil porosity n and volumetric stiffnesses of pore water K_w and soil grains K_s as:

$$\frac{1}{Q} = \frac{n}{K_w} + \frac{1-n}{K_s} \qquad (2)$$

(ii) The balance of linear momentum for the mixture soil skeleton–pore fluid, given by:

$$\rho \frac{D^{(s)} v_s}{Dt} = \rho \cdot b + div\,\sigma \qquad (3)$$

where ρ is the density of the mixture, *b* the body forces and σ the Cauchy stress tensor.

Assuming that for flow-like landslides the average depths are small if compared with their length or width, it is possible to simplify the 3D propagation model described above by integrating its equations along the vertical axis.

In this way, the Biot-Zienkiewicz equations for non-linear materials and large deformation problems are coupled to various constitutive models (Bingham, Voellmy, Mohr-Coulomb, etc.), obtaining a 2D depth-integrated model, which presents an excellent combination of accuracy and simplicity and provides information about propagation, such as average velocity or depth of the flow along the path.

The numerical model used for the mathematical problem's resolution is the smoothed particle hydrodynamics method (SPH). The SPH model is a mesh-free method that provides an interesting and powerful alternative to more classical numerical methods such as the finite elements method.

Smoothed particle hydrodynamics is based on discretized forms of integral approximations of functions and derivatives. The method has been introduced independently by Lucy (1977) and Gingold & Monaghan (1977) and applied to astrophysical modelling, a domain where SPH presents important advantages over other methods. The SPH method introduces the concept of 'particles', to which information concerning field variables and their derivatives is linked.

In particular, smoothed particle hydrodynamics method is based on the possibility of approximating a given function $\phi(x)$ and its spatial derivatives by integral approximations defined in terms of a kernel. In a second step these integral representations are numerically approximated by a class of numerical integration based on a set of discrete point or nodes, without having to define any "element".

The crucial point for simulation of the landslide is therefore to correctly define the rheological model used for the equivalent fluid.

PHYSICAL MODEL

This paper is part of a wide research developed in the frame of a National Operative Research Project (PON 01_01869) on the study of geosynthetic reinforced earth structures' behaviour subjected to debris flow impact, currently in progress at the "Mediterranea" University of Reggio Calabria. The aim of the research has been to design a large-size flume in order to simulate debris flows propagation.

The physical model, designed on the base of numerical simulations' results illustrated in this paper, consists of four main parts (Fig. 1).

(i) The principal structure is a steel flume 8 m long and inclinable, respect to the horizontal direction, with inclinations ranging between 20° and 45° evaluated according to the slope inclinations of real debris flows on granular and weathered cohesive soils (Gullà *et alii*, 2004, 2006), occurred in Calabria. The flume dimensions have been suitably selected in order to simulate, at the bottom of the flume, flow velocities comparable to those ones reported for debris flows in the scientific literature (Rickenmann, 1999).

(ii) A tank 2.5 m high, with a rectangular section 0.5 m x 1.5 m and with a sloping base that can be removed, is placed at the top of the flume.

(iii) The physical model is equipped with two additional independent structures: a structure for lifting the tank to the various heights of test, 8.86 m high, and a reticular structure for the lifting of the walkway necessary for tank's inspection.

(iv) The flume has side walls formed by transparent panels to allow the framing of the debris flow phenomenon using high definition video cameras. The phenomenon of propagation will be monitored by pressure transducers, located on the base of the flume, and by ultrasonic level sensors supported by joists or aluminium profiles, orthogonally positioned to the bottom of

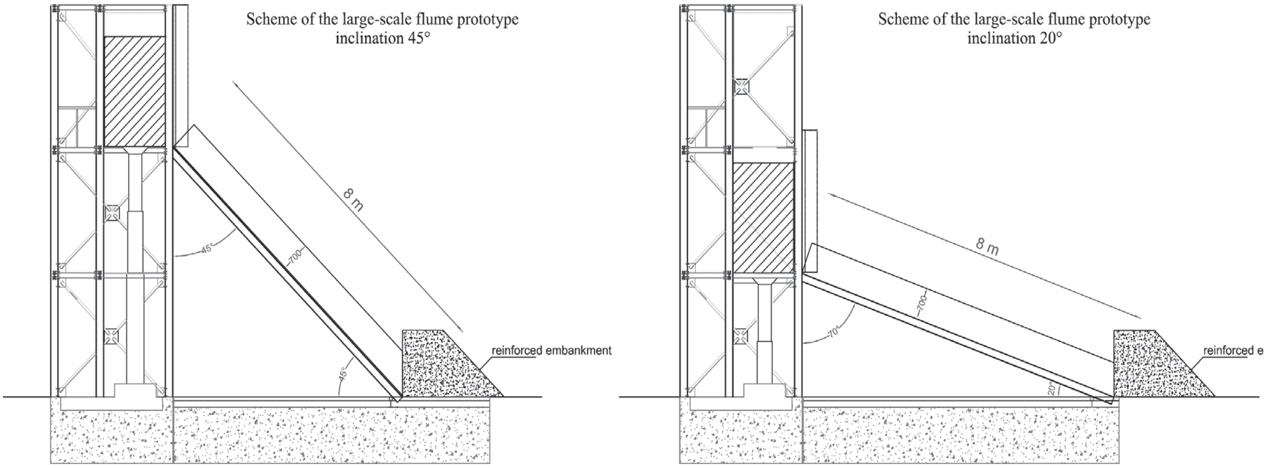


Fig. 1 - Schemes of the physical model

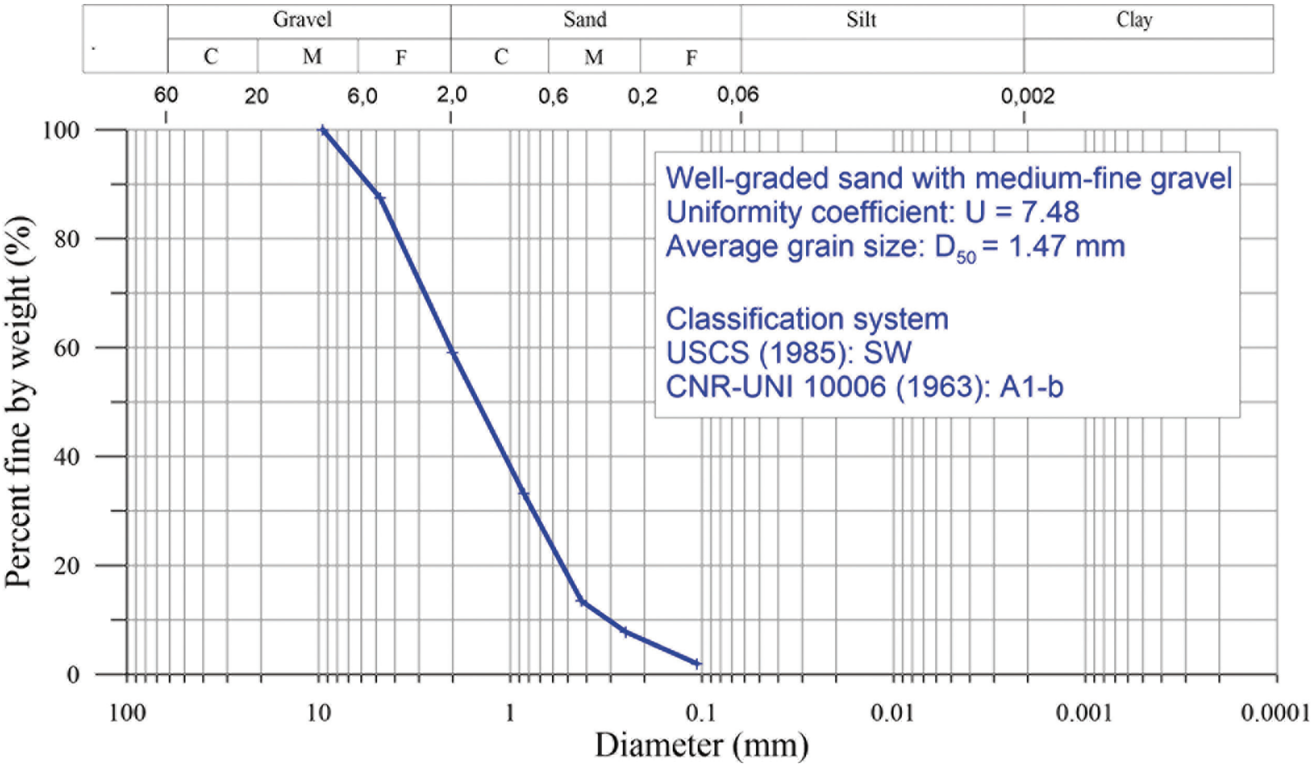


Fig. 2 - Grain size distribution of soil

the flume at the same sections where the transducers are located.

The test procedure consists of filling the tank with a granular soil-water mixture (at different concentrations); the mixture is instantly released, through the rapid opening of a gate, in order to reproduce the "dam break" trigger mechanism.

In the tests which will be carried out in the research, it has been chosen to use water-soil mixtures, whose solid matrix has the grain size distribution shown in Fig. 2. The soil is a well-graded sand with medium-fine gravel, classified as SW, according to USCS classification system, and as A1-b, according to CNR-UNI 10006 classification system, with grain shape from sub-rounded to rounded, uniformity coefficient U=7.48 and average grain size D_{50}=1.47 mm.

CALIBRATION OF THE RHEOLOGICAL LAW FOR SELECTED MIXTURES

To identify the rheology of the selected mixtures, several laboratory tests have been carried out at the University of Padua (Italy).

The flume is L=2.10 m long (including the tank), B=0.25 m wide, with a slope of i=30°, and it has a rigid bottom. The triggering of the mixture propagation occurs by means of a removal gate (Fig. 3).

The experimental tests have been carried out using a constant solid volume of dry material (the same material that will be used in the large-size physical model) with different water volumes. From a constant solid volume of dry material corresponding to W_s=30 kg, the volumes of water have been increased in order to obtain the following solid concentrations by volume:

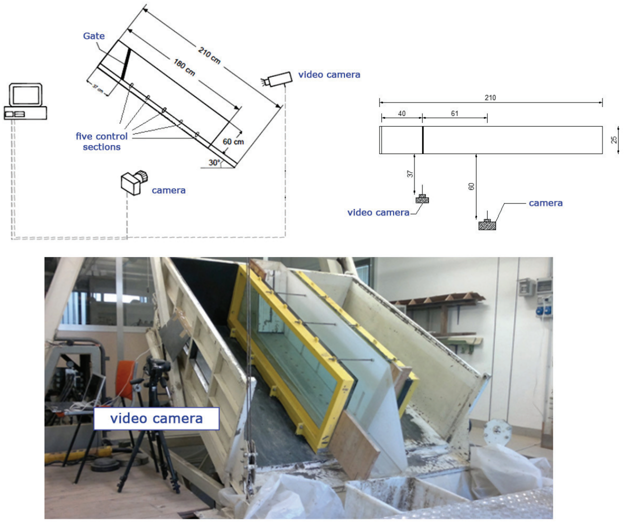


Fig. 3 - Flume test apparatus used to evaluate the rheological law of water-soil mixtures

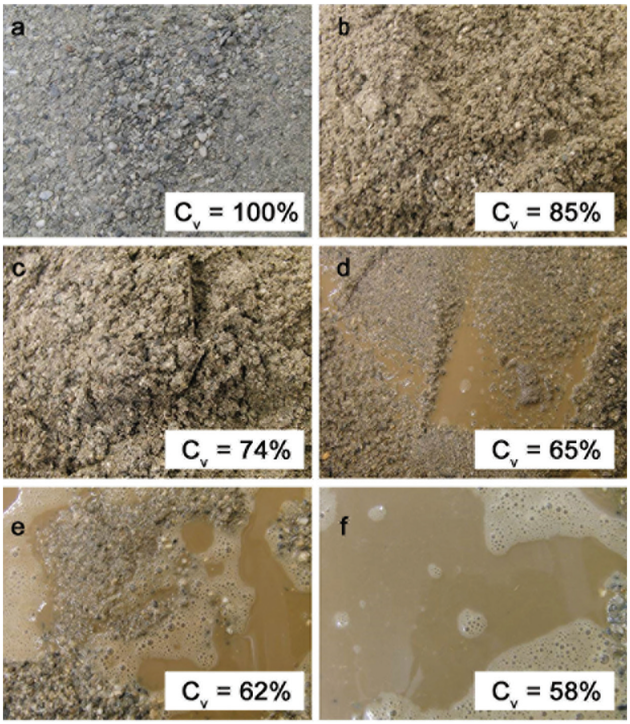


Fig. 4 - Different mixtures used in the research, varying the solid concentrations by volume

C_v = 85% (with 2 liters);
C_v = 74% (with 4 liters);
C_v = 65% (with 6 liters);
C_v = 62% (with 7 liters);
C_v = 58% (with 8 liters).

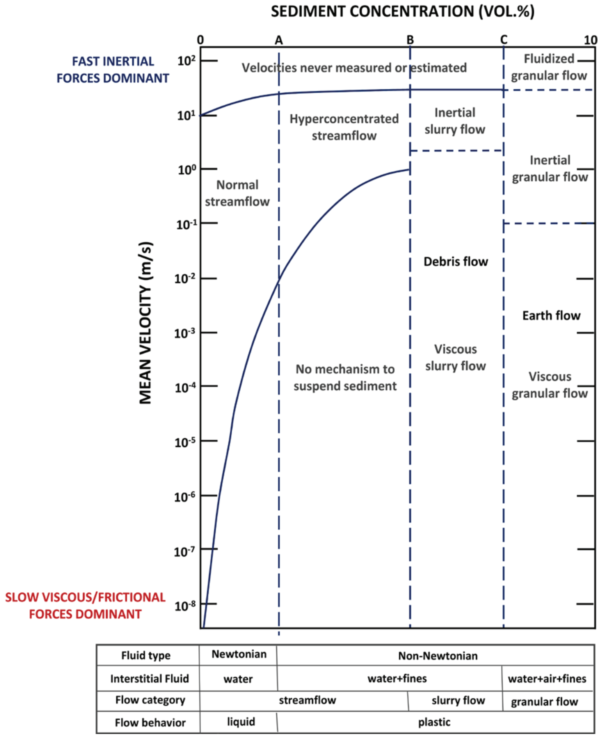
Figure 4 shows the different mixtures selected in the research, varying the solid concentrations by volume C_v. The solid concentrations by volume equal to 74%, 65% and 62% are those typical of debris flows, according to Pierson & Costa (1987) (Fig. 5).

The trends of flow front velocity over time, measured during the flume test, have been reproduced through different numerical analyses using the SPH code (Fig. 6). As it can be seen from the figure, for example for the volumetric solid concentrations 74% (Fig. 6a), 65% (Fig. 6b) and 62% (Fig. 6 c), the trend of the flow velocity over the time is quite reproduced.

It has been observed that the rheological model which best fits the behaviour of the used mixtures is the frictional model (Hungr, 1995). This model provides, in the case of flume with rigid bottom, the basal flow resistance stress according to Hungr equation (1995), as follows:

$$\tau = \rho g h (\cos i + a_c/g) \tan \phi \qquad (4)$$

with ρ = density of the flowing material; *h* = flow depth; *i* = slope angle; $a_c = (v^2/R)$ = centrifugal acceleration (resulting from the vertical curvature radius *R* of the flow path); $\tan \phi = (1-r_u) \tan \phi'$ bulk friction angle; r_u = pore pressure coefficient (ratio of pore pressure to total normal stress at the base of the block); ϕ' friction angle.



Fluid type	Newtonian	Non-Newtonian		
Interstitial Fluid	water	water+fines		water+air+fines
Flow category	streamflow		slurry flow	granular flow
Flow behavior	liquid	plastic		

Fig. 5 - Rheological classification of flows (Pierson & Costa, 1987)

Therefore, the numerical back-analysis of laboratory results has allowed to calibrate the parameter μ (=*tan* ϕ) , which controls the frictional rheological law (equation 4) (Tab. 1), and it was thus possible to find a correlation between friction angles and solid concentrations by volume of the mixture (Fig. 7). The figure shows that the friction angle of mixture sharply increases for C_v ranging from 58% to 65%, whereas the increase is less pronounced for C_v higher than 65% (typical values of mixtures where the solid matrix is predominant).

NUMERICAL ANALYSIS PERFORMED TO DESIGN THE PHYSICAL MODEL

For designing the physical model, an extensive parametric analysis has been carried out using the SPH code and the above mentioned frictional rheological law for the mixtures.

The purpose of the numerical analysis has been to evaluate the required length of the large-size flume in order to obtain the typical flow velocity of real events.

The parameters which have been varied are the length of flume, *L*; the inclination of flume, *i*; the released height of mixture, *H* and the friction angles of mixture, ϕ.

With respect to the friction angles of mixture ϕ, it has

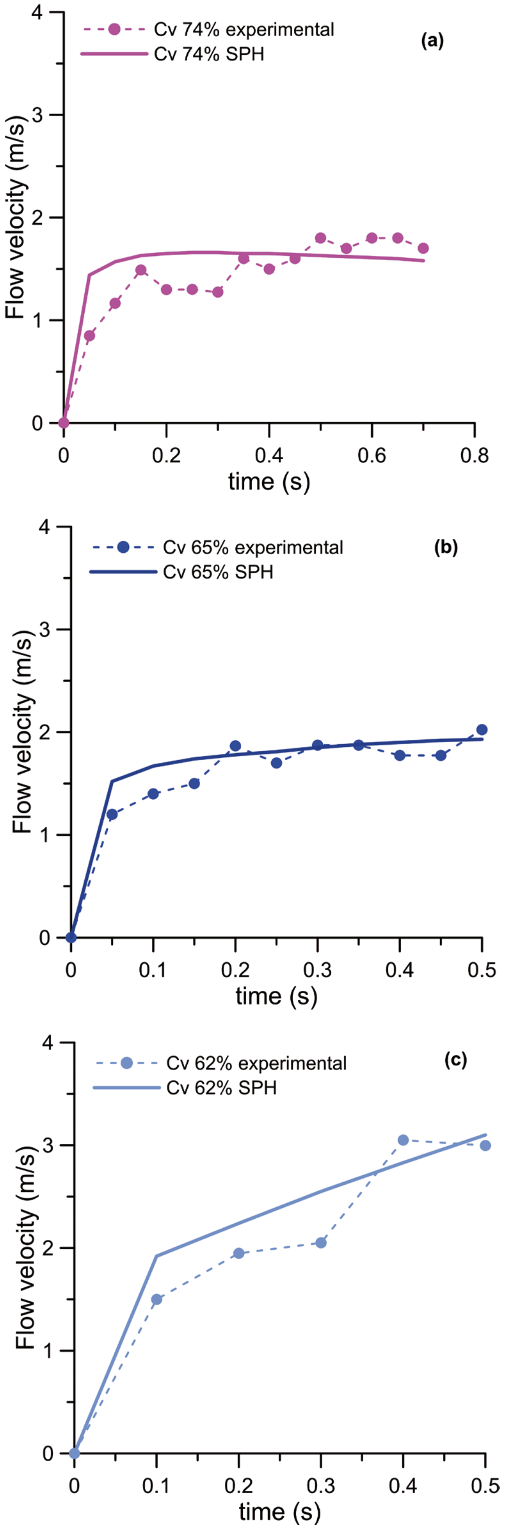


Fig. 6 - Flow front velocities: comparisons between experimental and numerical results for the different mixtures, C_v=74 % (a), C_v=65 % (b), C_v=62% (c)

Test	C_v solid concentration by volume	C_w concentration of water	ρ_m mixture density (kg/m^3)	ϕ friction angle (°)	μ friction coefficient
1	1	0	2670	36	0.727
2	0.85	0.15	2418	33	0.649
3	0.74	0.26	2232	31.5	0.613
4	0.65	0.35	2089	30	0.577
5	0.62	0.38	2029	20	0.364
6	0.58	0.52	1975	18	0.325

Tab. 1 - Friction angles of the mixture according to the different solid concentrations by volume

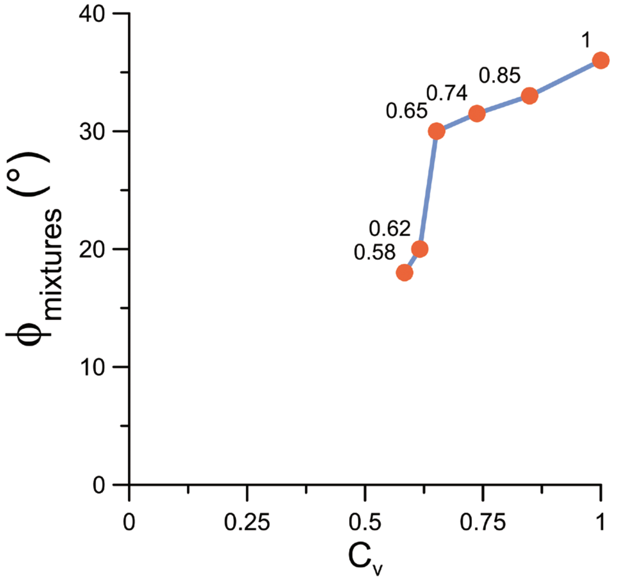


Fig. 7 - Friction angle values obtained by numerical analyses for the different mixtures

Length of the flume L (m)	Slope of the flume i (°)	Released height of mixture H (m)	Friction angle of the mixture ϕ (°)	Rheological law
6-8-10	15-20-25-30-35	1-2	0-20-30-36	Frictional

Tab. 2 - Parameters considered in the numerical analysis

been chosen to investigate values corresponding to solid concentrations by volume typical of debris flows (ϕ=20°, 30°), the friction angle corresponding to the pure fluid (ϕ=0°) and the friction angle corresponding to the dry material tested in the current research (ϕ=36°) (Tab. 2).

In the parametric analyses, the released mixture has been placed at the top of the flume, inside a tank with a 45° inclined bottom. The tank's length is 1.5 m and the parametric analyses have been carried out for different values of released height of the mixture (i.e. *H=1 m* and *H=2 m*) corresponding to different mixture volumes, $V=0.25\ m^3$ and $V=0.94\ m^3$ respectively (Fig. 8).

Figure 9 shows the 1-D numerical analysis of mixture's propagation in flume at different times in the case of flume length *L=8 m*.

Figure 10, Figure 11 and Figure 12 show the trends of flow front velocities at the end of the flume versus the flume inclination for different values of mixture’s friction angle, in case of released heights *H=1 m* and *H=2 m*, considering three different lengths of flume equal to *L=6, 8 and 10 m*.

As expected, the flow velocity increases with increasing flume inclination. Besides, at the same value of flume inclination, the flow velocity decreases with increasing mixture friction angle.

It can be noticed that the same value of flow velocity can be obtained with different combinations of mixture friction angle and flume inclination.

Figure 13, Figure 14 and Figure 15 show the flow heights at the end of the flume versus the flume inclination for different values of mixture’s friction angle, in case of released heights *H=1 m* and *H=2 m*, considering three different lengths of flume equal to *L=6, 8 and 10 m*.

It can be noticed that the height of the flow increases with increasing the inclination and, at the same inclination, it decreases with increasing the mixture friction angle.

By analizing the numerical results in the range of debris flow typical slopes ($i \geq 35°$) and solid concentrations by volume (friction angles), in the case of lower released height of mixture (*H=1 m*), the characteristic velocities of real debris flows ($v > 5$ *m/s*) can be obtained with a flume having length equal to *L=8 m*. Therefore, it has been chosen to design a 8 meters long physical model.

CONCLUSIONS

The study has provided relevant results for the design of the large-size physical model.

Regarding the rheological law used in the numerical analysis, several laboratory tests have been carried out. The test results have shown that the model which best fits the behaviour of the selected mixtures is the frictional law.

Moreover, the numerical back-analysis, performed to reproduce the experimental results, has allowed to find a correlation between friction angles and solid concentrations by volume of the mixtures.

Afterwards, the frictional law has been used in the numerical analysis to reproduce the typical velocities of debris flows.

The numerical analysis has been carried out varying different parameters. The obtained results have shown that, considering

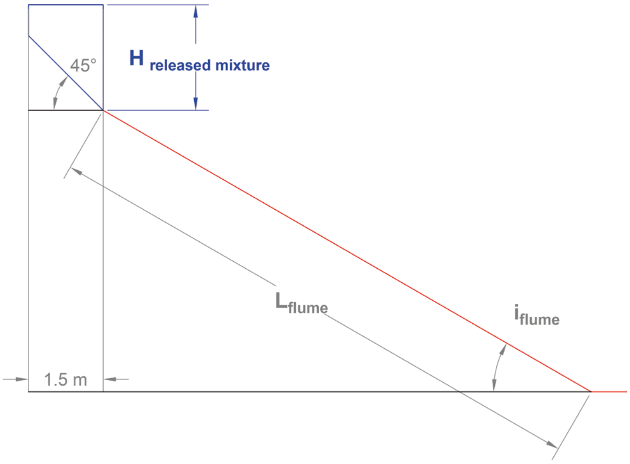


Fig. 8 - Scheme of large-size physical model used in numerical analysis

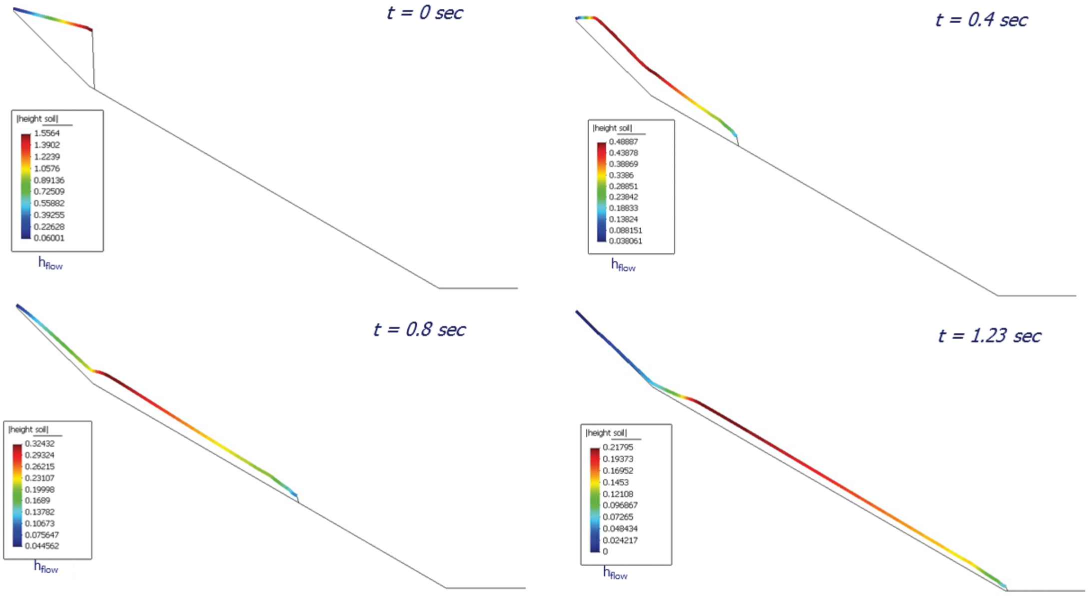


Fig. 9 - 1-D numerical analysis of mixture’s propagation in the large-size physical model at different times in the case of length L = 8 m

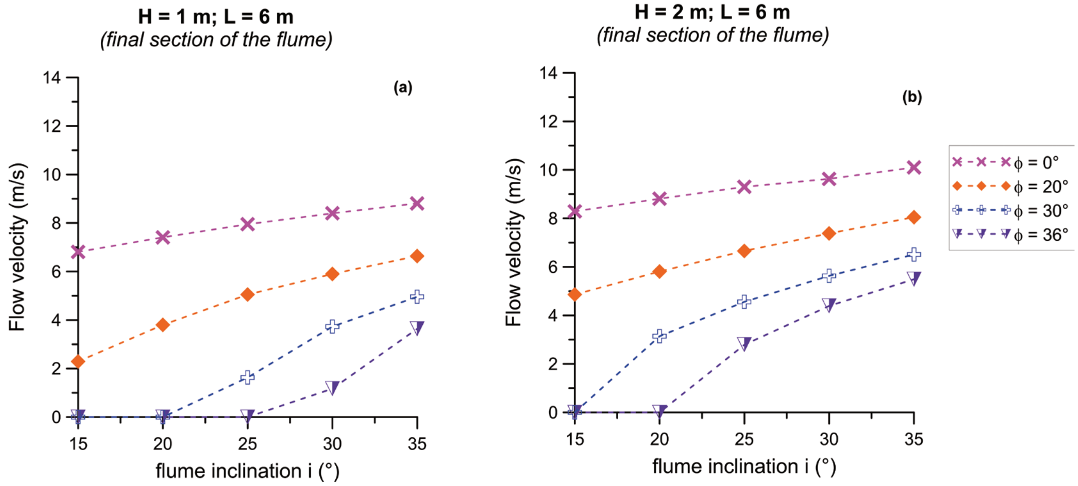


Fig. 10 - Flow velocities versus physical model inclination, for length L=6 m, in the case of released height: (a) H=1 m and (b) H=2 m respectively

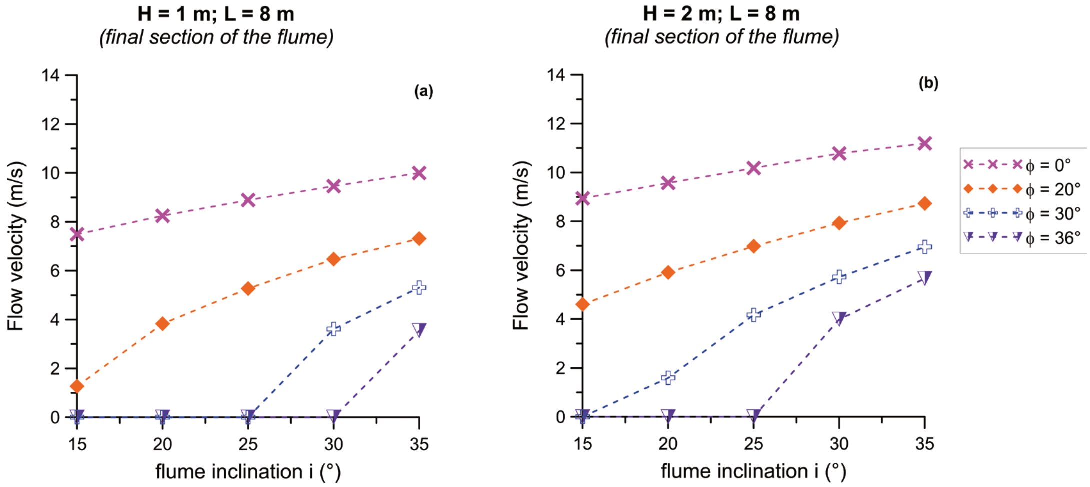


Fig. 11 - Flow velocities versus physical model inclination, for length L=8 m, in the case of released height: (a) H=1 m and (b) H=2 m respectively

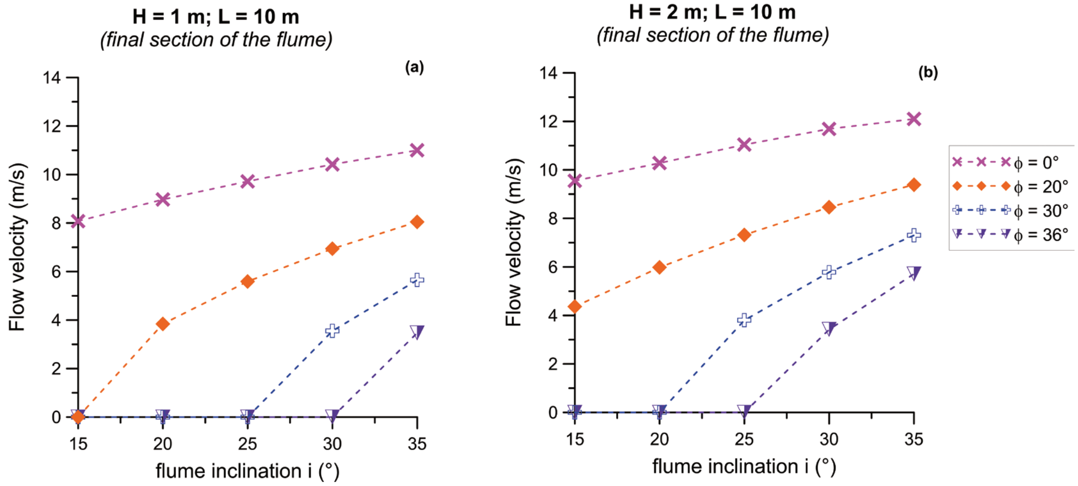
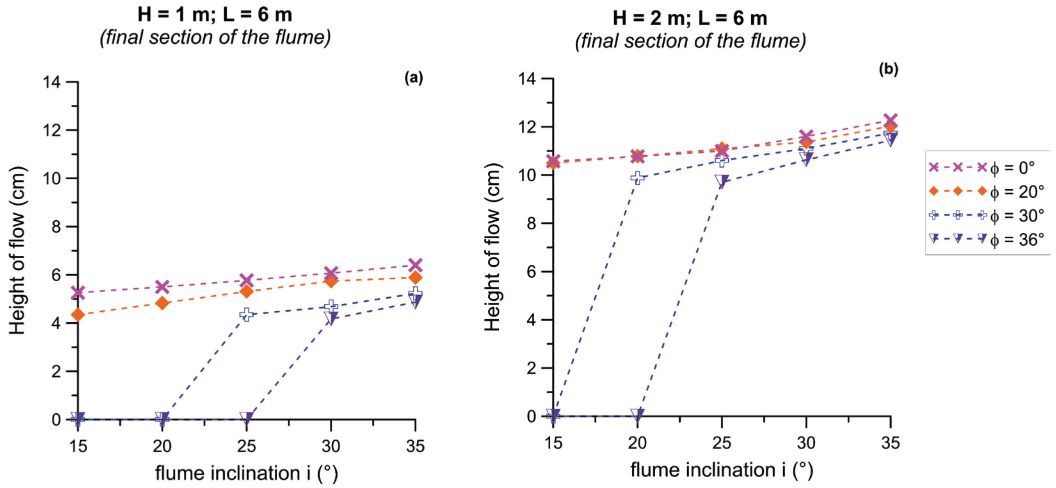


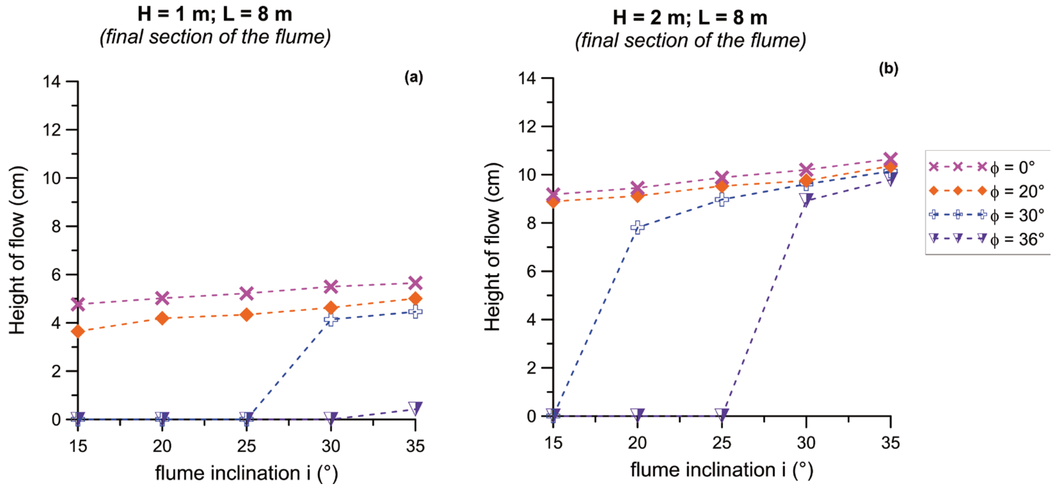
Fig. 12 - Flow velocities versus physical model inclination, for length L=10 m, in the case of released height: (a) H=1 m and (b) H=2 m respectively



H = 1 m; L = 6 m
(final section of the flume)

H = 2 m; L = 6 m
(final section of the flume)

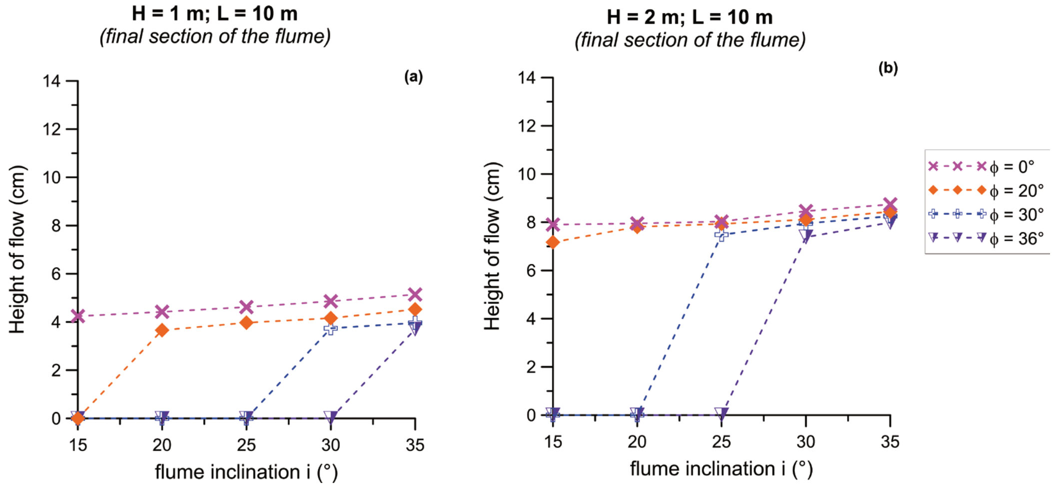
Fig. 13 - Height of flow versus physical model inclination, for length L=6 m, in the case of released height: (a) H=1 m and (b) H=2 m respectively



H = 1 m; L = 8 m
(final section of the flume)

H = 2 m; L = 8 m
(final section of the flume)

Fig. 14 - Height of flow versus physical model inclination, for length L=8 m, in the case of released height: (a) H=1 m and (b) H=2 m respectively



H = 1 m; L = 10 m
(final section of the flume)

H = 2 m; L = 10 m
(final section of the flume)

Fig. 15 - Height of flow versus physical model inclination, for length L=10 m, in the case of released height: (a) H=1 m and (b) H=2 m respectively

the ranges of solid concentrations by volume and the slope inclinations typical of real debris flows, the velocities reach the debris flows values in the case of flume length equal to *L=8 m*. Thus, the numerical analysis has allowed to design the length of the large-size physical model.

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