Internationales Symposion
INTERPRAEVENT 2004 – RIVA / TRIENT

DESIGN CRITERIA OF MUDFLOW BREAKERS

EXPERIMENTAL AND THEORETICAL APPROACH

Aronne Armanini, Claudio Dalrì, Federica Della Putta, Michele Larcher, Luca Rampanelli & Maurizio Righetti[1]

ABSTRACT

The phenomenon of debris and mudflow is of much interest nowadays for the major economical and social development of mountain regions. The purpose of this paper is the formulation of a criterion for designing mudflow breakers, structures that are usually located inside a deposition basin or upstream of a slit check dam in order to reduce the destructive power of mudflow and debris flow and to localize dissipative and scouring phenomena in limited areas. In particular we focalise the analysis to the specific case of deposition basins, where the insertion of mudflow breakers permits to minimize the part of the bottom of the basin to be protected, reducing negative environmental impacts and building costs. The investigation was carried out both theoretically and experimentally, taking into account the effect of fluid viscosity and concentration in the realization of a reduced scale model. Results provide for the positioning of mudflow breakers in two rows being sufficient to dissipate most of the kinetic energy of the incoming debris flow.

Key words: mudflow, debris flow, mudflow breaker, energy dissipation.

INTRODUCTION

In the technical literature there are few references about mudflow breakers design criteria. Some simple criteria were mentioned by Baldwin *et al.* (1987), concerning some defence structures built in the San Francisco Bay. The authors suggested the construction of breakers composed by small elements of wood, steel or concrete, dimensioned to bear the impact forces. They are fixed in the terrain with concrete foundations, with a lateral spanning of 2 or 3 m. In general the relative position of the elements, the distance between two elements and the number of rows are defined on the basis of the morphology and the characteristics of the catchment; moreover, to increase the resistance to the flow, every single element can be connected to the others by chains or metallic nets.
Because of the shortage of information on mudflow breakers, the problem is studied here by means of an experimental approach on physical model. In the construction of the hydraulic model, the choice of the type of material to be employed is very important as, in the case of mudflows, both the stress regime and the dissipative processes have characteristics completely

1 CUDAM - Dept. of Civil and Environmental Engineering, University of Trento, via Mesiano 77, I-38050 Trento, Italy

different with respect to the case of clear water, though affected by ordinary sediment-transport phenomena. Generally a distinction has to be made on the rheological characteristics of the mixture, which presents a remarkable variability as a function of the solid-phase concentration. An important parameter to be taken into account in mudflow breaker design is the solid concentration. The mudflow characterized by relatively low values of the solid phase concentration shows generally high velocities and small flow depths: in this case the dynamic impact on the blocks can be particularly devastating. On the other side, mudflows with relatively high solid concentration are characterized by thick flow depths and low flow velocities that may lead to overflow problems. (Armanini *et al.*, 2001).
The estimation of the correct concentration that could occur during a mudflow event is the focal aspect to be evaluated in order to test the efficiency of a defence structure.
Herein the experimental investigation on different kinds of mudflow breakers is presented. The aim of the experiments is to verify that for low concentration of the fluid the interventions effected were able to locate the dissipation of most of the energy in a localized area, so as to reduce the costs for the construction of the works without compromising the overall security level obtained. Moreover the works must be able to spread out the more dense flows inside the area destined for the accumulation, blocking the regular flowing of the possible subsequent flood event and the consequent flooding of upriver areas.

PHISICAL MODELLING OF DEBRIS- AND MUDFLOW

Physical modelling on reduced scale of structures against debris flow is not very diffused; this procedure could be justified in the past because the cost of this kind of defence works was lower than other hydraulic structures. On the contrary, nowadays it is recommended to perform physical modelling for safety reasons. Physical modelling is at present the most reliable tool in order to verify these structures; however the problems which physical modelling involves are not easy to solve and the determination of the proper similarity law is not a simple task. Scientific literature reports a number of approaches, although a general agreement on all issues is still lacking. Even if debris flow is to be considered an unsteady phenomenon, similarity laws are obtained by the general equations relevant to steady one-dimensional flow of a homogeneous fluid, with average density ρ, and to the mass conservation. On the contrary, from a theoretical point of view, the density of the mixture is a function of space and time; experimental evidence has however demonstrated that, for the purpose modelling, density variations along the path are of minor importance, so that the density can be considered as a constant. Following this approximation, it is possible to obtain a uniform flow formula of the mixture, suitable to obtain the similarity rule. In fact if the fluid is not clear water but mud, viscosity plays a role that is not negligible with respect to inertia and gravity, therefore in mudflow modelling it is necessary to satisfy simultaneously Froude and Reynolds similarity criteria. Moreover it should be noted that a modified expression $g' = g\,(C\Delta + 1)$ should be utilized for the gravity acceleration in evaluating the Froude number (Armanini, 1991), with C volume concentration of the solid phase, $\Delta = (\rho_s - \rho) / \rho$ relative density of the solid phase and g gravity acceleration. In literature there are many expressions relating the relative viscosity of the mud with the volume concentration. Equation (1) represents the expression proposed by Krieger (1972), in which μ is the viscosity of clear water, μ_m the viscosity of mud and C^* the maximum possible volume concentration of the solid phase.

$$\frac{\mu_m}{\mu} = \left(1 - \frac{C}{C^*}\right)^{-1.82} \tag{1}$$

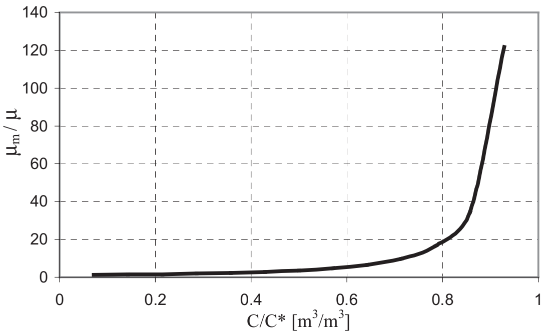


Fig1: Specific viscosity of the mud (Krieger, 1972).

In Fig1 it is possible to notice how the relative viscosity of the mixture increases for increasing concentrations.

In order to satisfy simultaneously Froude and Reynolds similarity, equation (2) has to be satisfied, where λ is the geometric scale reduction of the physical model, λ_ρ represents the scale reduction of the mixture density, λ_d represents the scale reduction of particle diameter and λ_μ represents the scale reduction of the mixture viscosity.

$$\frac{\lambda_\rho \lambda^{1/2} \lambda_d}{\lambda_\mu} = 1 \qquad (2)$$

From equation (2) it emerges that in physical modelling of debris- and mudflow it is usually necessary to use a material with a characteristic diameter less reduced respect to the geometric scale of the model, in order not to obtain too high and not realizable scale reduction values of λ_μ.

EXPERIMENTAL APPARATUS

The experimental apparatus was composed of a rectangular tilting channel, 40 cm wide and 2 m long, that flows into a 140 cm wide, 2 m long tank (Fig2). The fluid was recirculated through a properly designed closed circuit system, able to produce steady-flow conditions inside the model. The hydraulic model represented a mountain valley leading into a stilling basin. All the tests with clear water were performed according to Froude similarity, while those with mud respecting also Reynolds similarity. The channel was long enough to assure uniform flow conditions before entering into the stilling basin. The experiments were done both with clear water and mudflow: in particular experiments performed with clear water, the extreme case of low concentrations, enabled to highlight the erosive capacity of the current. In the first case the discharge was fixed (Q = 0.018 m^3/s) and the Froude number of the in-flow channel was varied tilting the channel. In the second case three different mudflow concentration were tested (c_1 = 24%, c_2 = 28%, c_3 = 40%): for each concentration the discharge was constant (Q = 0.018 m^3/s) and only the Froude number was changed. Some preliminary tests were carried out both in movable bed and fixed bed conditions. Concerning the tests on movable bed four uniform granular materials were used with different diameters: d_{50} = 50 mm, d_{50} = 31 mm, d_{50} = 10 mm and d_{50} = 4.4 mm.

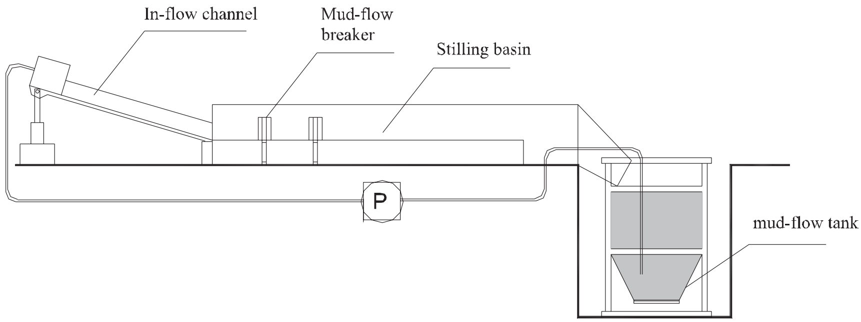


Fig2: Scheme of the experimental apparatus.

MEASURING TECHNIQUE

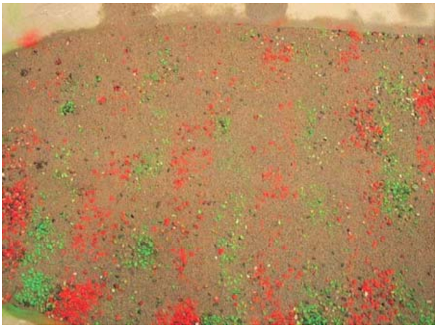
To calculate the value of the specific energy, the flow depth was measured by means of a point gauge placed on a trolley movable both in the longitudinal and transversal direction. The hydrodynamic field has been surveyed through the reconstruction of the trajectories, obtained tracking tracers floating on the surface of the fluid. To this purpose, a digital high-speed CCD camera was used, shooting from above of the motion field. The position of the particle centroids has been detected with sub-pixel precision (1/84 *pxl*). For the reconstruction of the trajectories covered by the centres and the subsequent assessment of the particle velocity, an opportunely modified version of the Particle Tracking Velocimetry algorithm by Hassan & Canaan (1995) was used (Serafini, 2003). The investigated flow field has been divided into 8 sub-shots, captured in subsequent times, in order to increase the spatial resolution of the measured velocities. The statistical ergodicity of the stationary-motion field examined permits the reconstruction of the whole flow field coupling the data measured for each shot. Afterwards, starting from these data, the specific energy associated with the section of interest was calculated.
The analysis of the digital images allows the determination of the streamlines and the calculation of the length of the rollers and the depth of the lateral jets formed by the breakers.
A system of load cells has been developed and used, able to measure the force exerted by the flow on the breakers with a confidence interval ranging between 0.3% and 0.6%.

RESULTS

Results in mobile bed configuration

Some initial tests, carried out on a movable bed composed by uniform grain size material, leaded to show that high density mudflows tend to form a deposition layer over the erodible bed near the entrance of the stilling basin, preventing in this area the bed from any successive erosion.

a)



b)

Fig 3: Striped coloured bed of the sedimentation basin: a) before the experimental run; b) after having carefully removed the mud at the end of the test.

However if the mud is not sufficiently dense a localized scouring should form. In this case it is necessary to design structures able to localize this phenomenon to mitigate possible damages. The results of the experimental analysis allowed concluding that the optimal arrangement of the flow breakers provides for a system composed by several rows of breakers disposed normally to the undisturbed velocity direction.

Fig4: *M30-d1* type mudflow breakers.

The first one has the function of deviating the current, while the second one reduces significantly the available cross section of the basin and enhances the transition of the flow into sub-critical conditions. The successive rows have the function to absorb possible jets, which are likely to form.

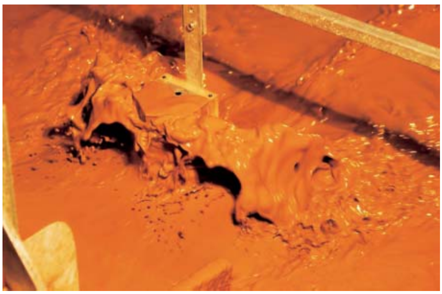


Fig5: Comparison between the hydraulic effect induced by a *M30-d1* mudflow breaker (left) and a *M120-d1* one (right).

Results in fixed bed configuration

The purpose of this series of experiments is to evaluate the dissipation efficiency of the breakers, as a function of the characteristics of the flow and of the blocks geometry. In order to pursue this aim, different geometries of breakers (Fig6) and different configurations have been tested. Two different cases have been observed:
- if the deviation angle is small enough ($\theta < 45°$, where θ is represented in Fig6), two lateral jets form;
- if the deviation angle is large enough ($\theta > 45°$) a third vertical jet forms, which overtakes the breaker.

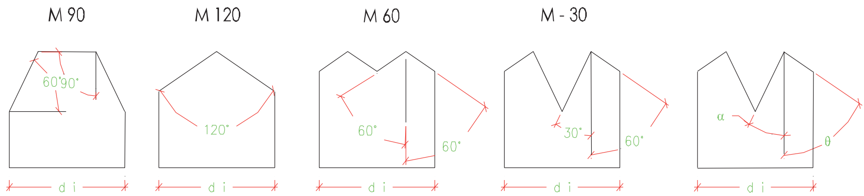


Fig6: Schematic representation of the various typologies of breakers used in the experiment.

Moreover it has been observed that:
- a single wedged breaker, as the M-120 type in Fig6, is not suitable to deflect the incoming flow, because it induces the formation of strong lateral jets. Moreover, the addition of one more then a single wedged breaker, the problem is not resolved: locally each breaker behaves as described above;

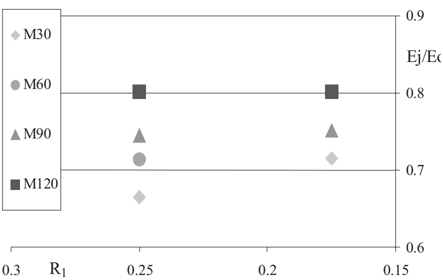


Fig7: Dissipative effect of the first row of breakers as a function of the local narrowing ratio R_1 for a Froude number of the incoming current equal to 2.5. E_j is the specific energy of the current measured using various types of breakers.

- the double wedged blocks, as the M-30 type in Fig6, force the formation of a roller just upstream the breaker and this causes a strong reduction in the jets dimension, so leading to a significant reduction of the extension of the localized scouring zone and an increase in energy dissipation;
-the shape and the location of the hydraulic jump are influenced by the shape and arrangement of the first row of breakers.

Moreover, the performed analysis allows evaluating the optimal location (i.e. the one able to maximize energy dissipation) for the first row of breaker, in order to characterize the extension of the area interested by erosion, and to quantify the flow overpressures on the defence structures.
The determination of the dissipative capacity of the system has been calculated in a section just downstream the breakers and by calculating the specific energy of the flow in that section. It is possible to define a non-dimensional parameter E_j/E_0, in which E_0 represents the value of the specific energy in the reference section when mudflow breakers are not present, while E_j is the energy value of every configuration tested.

In Fig 7 the dissipation efficiency is presented for different kinds of mudflow breaker ($R_1=b_D/b_m$ where b_D represents the breaker width and b_m the width of the in-flow channel). The data refer to the clear water and incoming Froude number equal to 2.5. It is possible to note that:

- for breakers with a narrowing ratio $R_1 = 0.25$ the shape of the breaker employed determines significant difference in energy dissipation;
- considering simultaneously the two series of values, the *M30* shape allows to maximize the dissipative capacity.

From the considerations above the *M30-d1* is the most efficient breaker among those studied because of its capacity to damp the lateral flows and to dissipate the kinetic energy of the current.

In Fig 8 results are reported for a test performed in clear water with Froude number equal to 2, and for a test with a 24% volume concentration and a slope of the in-flow channel equal to 5%. Energy is dissipated above all by the first two rows of breakers, while the contribution given by the third row is negligible, therefore flow-breaker configurations composed by more than two rows can be considered not necessary. From Fig 8 it emerges that for a given flow-breaker less kinetic energy is dissipated by mudflow than by clear water. One possible explanation of this is that, due to the small scale, in the mudflow case the fluid viscosity influences the flow, while in clear water Reynolds number is high enough for the flow to be independent on it.

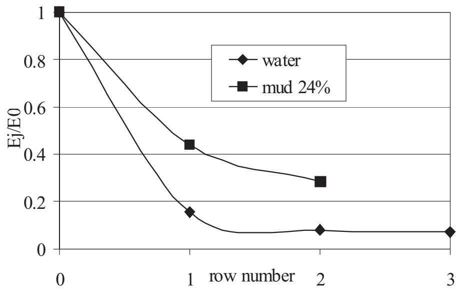


Fig8: Relative energy dissipation produced using different numbers of rows of flow breakers in the presence of a mud flow with concentration equal to 24% and in the presence of water. The specific energy was measured in a cross section different then the case presented in figure 7.

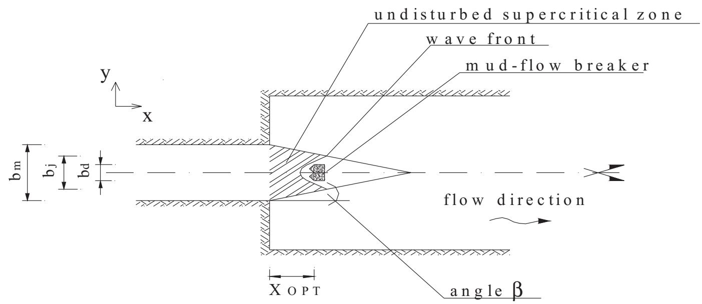


Fig9: Constant supercritical flow fields at the confluence. The angle β of the characteristic decreases for increasing Froude numbers.

In designing these works, it is very important to know the zone of the basin where the dissipative phenomena take place, in order to protect the foundation of the structures from possible scouring. The minimum distance $X_{OPT,}$ at which placing the first row of breakers in order to minimize the lateral jets and maximize the energy dissipation, has been determined by the following procedure:

- the breaker with shape *M30-d1* has been positioned at different distances from the outlet of the upstream channel inside the area where the in-flow stream is not yet affected by the section widening, according with field theory of supercritical flows (*Knapp & Ippen, 1938*);
- the intensity of the lateral jets depends also on the difference between the width of the undisturbed field b_j (linearly decreasing in the downstream direction) and the width of the block b_d;
- for $Fr_1>1$ the following empirical formula has been obtained for X_{OPT}:

$$\frac{X_{OPT}}{b_D} = 0.69 Fr_1 - 0.59 \tag{3}$$

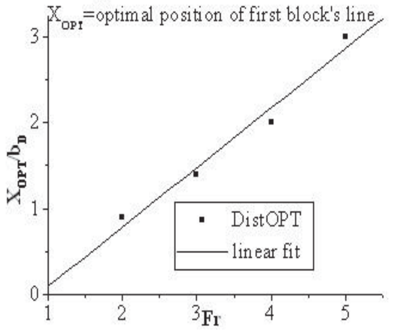


Fig10: Relation between the Froude number and the ideal distance X_{OPT} from the inlet-channel outlet at which the breaker has to be placed.

The impact of a flow against the block can be assimilated to the impact of a debris surge against a vertical wall. In this case two types of impact have been observed by Armanini & Scotton (1993): either a vertical jet or a reflected wave. In the experiments we noted that the presence of the breakers enhanced the formation of a phenomenon, which can be considered neither a reflected wave nor a vertical jet. The problem has a two-dimensional characterization, and further experimental investigations are needed for a deep comprehension of this phenomenon. In this case, however, our interest is limited to define the extension of the zone subjected to erosion. For this reason a simplified approach has been proposed with reference to the rollers of an hydraulic jump studied by Hager (1990), which is a case quite similar to the one presented here. The expression proposed by Hager is:

$$\frac{l_r}{h_1} = 160 \cdot \tanh\left(\frac{Fr_1}{20}\right) - 12 \tag{4}$$

with the following limits of validity:

$$\begin{cases} 2 \le Fr_1 \le 16 \\ \dfrac{h_1}{b_m} \le 0.1 \end{cases} \tag{5}$$

where l_r is the roller length; h_1 the upstream flow depth; Fr_1 is the Froude number of the upstream current and b_m is the inflow channel width.
According to this procedure, the length of the roller is independent from the type of the breaker. For this reason the theoretical length l_r has been corrected with a reduction coefficient k, defined as:

$$k = \frac{l_{r\_CALC}}{l_{r\_MIS}} \tag{6}$$

in which l_{r_CALC} is the roller length calculated utilizing relation (4) and l_{r_MIS} is the measured value.
The value of k is a function of the main parameters of the problem: namely of the shape factor represented by the internal shape angle α (Fig6), by the Froude number of the incoming current

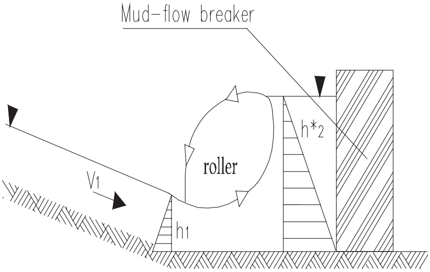


Fig11: Representation of the roller forming upriver with respect to the flow breaker.

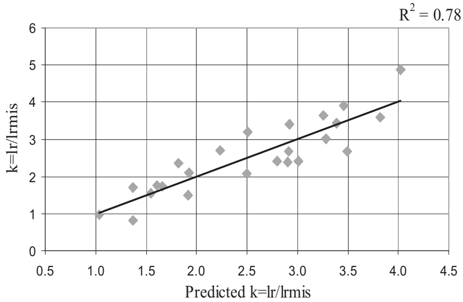


Fig12: Comparison between the calculated and measured values of k.

Fr_1 and by the dimensionless contraction ratio $R_1=b_D/b_m$. The following empirical relation has been obtained for the coefficient k:

$$k = -[0.17 + 3.7 \cdot \ln R_1 \cdot \sin\alpha - 1.9 \cdot (\ln R_1)^3 \cdot \frac{\sin\alpha}{Fr_1}] \tag{7}$$

with the following limits of validity:

$$\begin{cases} 2 \le Fr_1 \le 5 \\ 0° \le \alpha \le 90° \\ R_1 < 1 \end{cases} \tag{8}$$

In Fig12 the experimental values of the reduction coefficient are compared to the theoretical ones given by equation (7). Inserting equation (7) into (6) and (4), the following formula is proposed for the length of the area interested by the roller and, therefore, to be protected:

$$\frac{l_r}{h_1} = \frac{160 \cdot \tanh\left(\frac{Fr_1}{20}\right) - 12}{k} \tag{9}$$

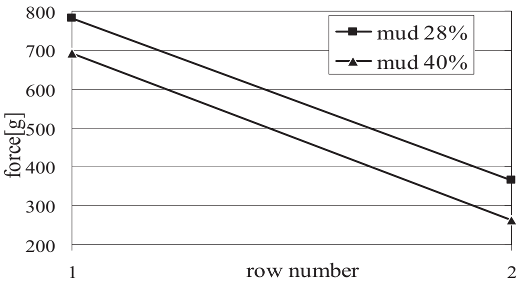


Fig13: Comparison between the mean values of the forces acting on the different rows of breakers produced by a mud flow with volume concentration equal to 28% and to 40%.

An analysis of the forces acting onto each breaker has been carried out in order to optimize the structural design of the works. This analysis allows determining a dimensionless parameter c_d (drag coefficient of the structure) to be adopted for design purposes. The mean values of the forces acting onto both rows are greater in the case in which the works are affected by a flow with lower concentration, according to the hypothesis of possible influence of Reynolds number (Fig13). The relation adopted is the following:

$$S = c_d \rho A \frac{v_1^2}{2} \tag{10}$$

in which $A=b_d\ h_1$ represents the main section; b_d the breaker width; h_1 the flow depth of the upriver current; v_1 the velocity of the undisturbed upriver current; ρ the density of the fluid; S the pressure onto the breaker and c_d the resistance coefficient.

In principle c_d should depend on the shape of the structures, on the geometrical characteristics of the in-flowing current and on Reynolds number. Fig13 shows a decreasing of impact forces for increasing mud concentration. This fact suggests that the increasing of Reynolds number produces an increasing of impact forces and this result agrees with the possible influence of Reynolds number on drag coefficients. The same figure suggests that the clear water should determine the highest force values. For this reason clear water has been considered the most severe condition. In Fig14 the clear-water drag coefficient for the first row of breakers has been reported as a function of Froude number: the experiments in clear water condition correspond to $Re > 10^4$, for which c_d should depend no more on Reynolds number.

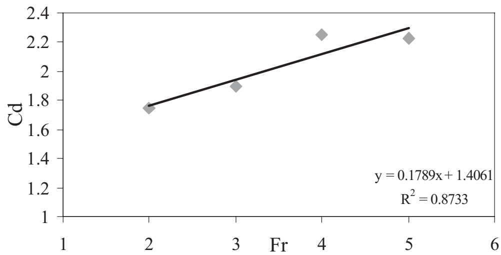


Fig14: Drag coefficient for the first row of breakers: peak impact forces.

From the data analysis the following linear equation is derived, obtained with clear water for $Fr_1>1$. It should be noted that the expression is asymptotically independent from the Reynolds number:

$$c_d = 0.18Fr + 1.4 \tag{11}$$

CONCLUSION

In this paper a particular application of mudflow breaker design is proposed, while at this stage of the research it is not possible to give a general solution for all possible cases of mudflow breakers. In particular some indications are given for the design of mudflow breakers to be located at the entrance of a deposition basin. The most efficient configuration is composed by two rows of breakers. The role of the second row of blocks is capturing the jets formed by the first row. The shape of the first breaker results to be the most important parameter.

The use of the breakers permitted to reduce the zone to protect from erosion. The necessity to place the works at a definite distance from the inflow channel in order to optimise the functioning of the works was shown. A formula to calculate the extension of the dissipative processes upstream the first block is given.

The research presented in this paper was carried out thanks to financial support provided by the Struttura Commissariale per l'Emergenza Idrogeologica nella Regione Campania. The authors wish to thank prof. Pasquale Versace for his support and his precious discussion on some points.

REFERENCES

Armanini, A. (2001): "Verifica su modello fisico in scala ridotta di manufatti speciali, quali vasche di laminazione o dissipazione o di deposito delle colate di detriti e di fango, da realizzarsi in località San Felice a Cancello come piano rimodulato ex ordinanza commissariale N. 415/99". CUDAM - Department of Civil and Environmental Engineering, Trento University, Italy.

Armanini, A., Larcher, M., Fraccarollo, L., Papa, M. (2001): "Considerazioni sulla dinamica delle colate di fango e sulle opere per il loro controllo". *Forum per il rischio idrogeologico in Campania: fenomeni di colata rapida di fango nel maggio '98*, Napoli 22 giugno 2001.

Armanini A. & Scotton P. (1993): "On the dynamic impact of a debris flow on structures". *Proc. XXV IAHR Congress,* Tokyo, vol. B, paper n. 1221.

Armanini, A. (1991): "Physical modelling of debris-flow". *Proceedings of the international symposium on debris flow and flood disaster protection*, Vol. A, 1-8.

Baldwin II, J.E., Howard, F.D., Terry, R.H. (1987): "On debris flow/avalanche mitigation and control, San Francisco Bay area, California". In J.E. Costa & G.F. Wieczorek (eds), *Debris flows/avalanches: process, recognition, and mitigation*: 223-236. Colorado: The Geological Society of America.

Della Putta, F. (2003): "Analisi sperimentale dei dispositivi frangicolata". *M. Eng. Thesis*, University of Trento, Italy.

Hager H.W., Bremen, R., Kawagoshi, N. (1990): Classical hydraulic jump: length of roller. *Journal of Hydraulic Research*, 28, 591-608.

Krieger, J. S. (1972): "Rheology of monodisperse lattices". *Advance of Colloid Interface Science* 3:111-136.

Okamoto, K., Hassan, Y.A., Scmidl, W.D. (1995): New tracking algorithm for particle image velocimetry. *Experiments in Fluids*, 19, 342-347.

Knapp, R.T., Ippen, A.T. (1938): Curvilinear flow of liquids with free surfaces at velocities above that of wave propagation. *5th Int. Congress. Of Appl. Mech.*,Cambridge, Mass. 531.

Rampanelli, L. (2002): Verifica sperimentale per il controllo di colate di detriti. *M. Eng. Thesis*, University of Trento, Italy.

Serafini, A. (2003): Messa a punto di un sistema di Partile Tracking Velocimetry per la determinazione di campi di moto. *B. Eng. Thesis*, University of Trento, Italy.