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Article

Mudflows: Assessment of Energy Dissipation on an Experimental Bottom Grid Device

Francesco De Paola

Department of Hydraulic, Geotechnical and Environmental Engineering, University of Naples Federico II, via Claudio 21 Napoli, Italy; E-Mail: depaola@unina.it; Tel.: +39-081-768-3420; Fax: +39-081-593-8936

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Abstract: Grid devices with a terminal wall barrier have been widely used for dissipation of energy load of water piped from the outfall works of artificial reservoirs. The satisfactory results obtained have led to the commitment to usage of such devices, with good results even in the case of mudflows for which design criteria were suggested. In this study, the experimental results of an evaluation of pressure on a vertical terminal wall are shown with the evaluation of the overall hydrodynamic thrust. The correct evaluation of the dynamic impact of a mudflow front against a structure is an important task in its design procedure. The hydrodynamic drive calculated from the tests with corresponding theoretical model values derived has shown a good matching. According to the test and speed range detected, the maximum dissipation rate due to the wall was about 35% of the available total load.

Keywords: mudflows; energy dissipation; hydrogeological risk; bottom grid device

1. Introduction

Hydrogeological risk is, either directly or indirectly, a threat to mankind life, health and convenience; therefore the need of rational planning and careful management of the physical environment, through the implementation of suitable measures, both structural or not structural, in order to mitigate risks related to quick mudflows is essential [1].

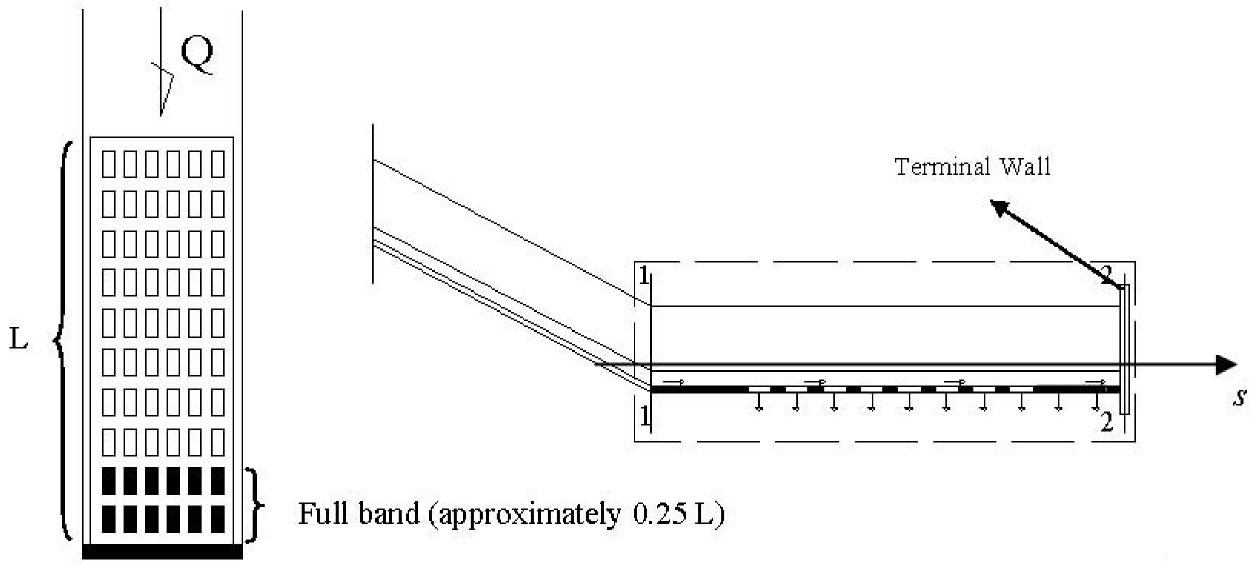
Works built to defend against landslides and mudflows have critical problems, especially compared to classical hydraulic works, due to lack of long experience and also because of the randomness in estimating the input needed to design them.

Among such works, bottom grid dissipators play an important role since they have already been used in surface outlets and/or bottom outlets in artificial reservoirs and their effectiveness for clear water flows has already been experimented on using suitably designed physical models in pioneering studies by [2,3].

In previous studies [1] the most effective configuration, among the various ones analyzed for the dissipation of the kinetic load of a mudflows, had: rectangular holes evenly located on the bottom of the parterre; with a full-empty ratio of about $\omega = 0.25$; a terminal wall as a barrier that significantly reduced the total length; and a full band of about 25% (Figure 1) [1] provided some preliminary sizing criteria for such a configuration.

In the present work, the results of an experimental survey aimed to assess the actual influence of a terminal wall on total energy dissipation that can be achieved by such a device, as well as hydrodynamic action around the terminal wall, are reported.

Figure 1. Experimental set-up scheme.



2. Dynamic Impact on the Terminal Wall: A Brief Literature Review and a Simple Formulation

Since the bottom grid device observed is surrounded by a vertical barrier wall to reduce total grid length and to achieve total disposal of the load coming from uphill, it is therefore interesting to study by means of a physical model in order to understand how the barrier wall helps dissipate energy.

Experiments on reduced scale physical models in literature are focused on the assessment of the impact of variously made mixtures against vertical walls. To this end [4] analyzed the impact of a mixture made of water and anionic resins; [5] studied the impact of water and grains; and [6], chose quick mud and sand flows.

With their differing approaches to the problem, they all studied the dynamics of the event, and each created a mathematic model summarized by a formula, allowing an estimation of the pressure applied to the vertical wall. This, together with experimental results, demonstrated the behavior of their chosen mix as a moving mass model, thus providing indications on parameters that influence the event, such as mix density, water front depth and speed.

On this matter, [7] undertook studies of the impact strength of flows like *debris flow* on vertical structures, arriving to the conclusion that it can be classified into two kinds according to the generation mechanism: one is generated when the solid portion of the flow hits the wall like bullets being fired against it (solid impact), thereby causing localized damage to the wall; the other one is when fluid mass impacts the wall, like a flood(fluid impact) destroying the wall because of the stronger impulse and larger impact.

According to literature, we can conclude that there are at least two types of moving stream, one average and one impetuous [8]. The average kind is due to the inertial component of the impacting flow, while the impetuous kind is due both to interstitial fluid and internal tension caused by the viscous matrix and solid particles contained within the fluid itself. Such behavior certainly corresponds to natural and devastating events that have occurred in the past, and allow to better understand the dynamics of the immense destructing effect of slides, in terms of damages to objects and people.

With regard to the first approach we can quote, for example, the formula elucidated by [4] who, by using a mixture made of water and anionic resins, calculated the impact strength f_I, per unit length [N/m], with reference to the stream front height h_m, as follows:

$$f_I = 9 \cdot \rho_m \cdot g \cdot \frac{h_m^2}{2} \tag{1}$$

A formula using the second kind of approach is the [6] one, who calculated the impact strength f_{II} [N/m] per unit of width, depending on hydrodynamic parameters in normal conditions, as height h_n and stream speed u_n, as follows:

$$f_{II} = k \cdot \rho_m \cdot h_n \cdot u_n^2 \tag{2}$$

where k is a constant that can have a value of between 5 and 12 and ρ_m is the mix density (g the acceleration of gravity).

In order to calculate an easy formula for our schematic of the grid device, the dynamic balance global equation was applied to the control volume between section 1-1 and 2-2, developed along the s axis (Figure 1).

Thanks to the application of this equation, it was possible to theoretically estimate the load on the barrier wall ($\prod_s$) [N], resulting in the following:

$$\Pi_{s\_2-2} = \left(\rho_m V_m^2 h b\right)_{1-1} + \left(\frac{1}{2}\gamma_m h^2 b\right)_{1-1} \tag{3}$$

where γ_m and ρ_m are respectively the specific weight and the mix density the slide is made of, h is the mudflow depth, b is the channel width and V_m is the average speed of the incoming fast flow.

To express such strength by width unit we must divide all members of (3) by b getting the following for f_G [N/m]:

$$f_G = \frac{\Pi_{s\_2-2}}{b} = \left(\rho_m V_m^2 h\right)_{1-1} + \left(\frac{1}{2}\gamma_m h^2\right)_{1-1} \tag{4}$$

3. The Experimental Setup: Bottom Grid Device with Front Terminal Wall

The experimental installation, described in detail in a previously mentioned paper (Figure 2) [1], is made of a steel tank, supplied with a mechanical mixer to provide a suitable homogeneity to the water and solid mixture. The system used to improve the mix homogeneity was made of a direct inlet on the ingoing piping so that, starting from the closed circuit pump group, the mix circulates forecefully around the vertical pump axis in a counterclockwise direction.

Figure 2. Experimental model.

In this way, any solid elements do not have enough time to fall on the tank bottom and the mix remains a homogeneous hyper-concentrate fluid feature.

For this reason, it is underlined that dynamic viscosity was kept constant within the gap from 0.20 Pa·s and 0.22 Pa·s (about 200 times clear water viscosity), which corresponds to a weight concentration of between 32% and 33%, while mix density was about $\rho_m = 1{,}362$ kg/m^3.

The 1000 L tank is supplied with a special pump, made by a pump manufacturer by the name of TUROITALIA, capable of 30 L/s mudflow, with a maximum prevalence of about 12 meters and an installed power of about 18.5 kW (Figure 2).

At the end of the grid there is the vertical barrier wall which allows, mainly for bigger flows, complete disposal (outflow) into the underlying steel drain (Figure 3). This drainage guides the mudflow into the steel tank allowing its recirculation.

Figure 3. Analyzed bottom grid dissipator.

In order to measure hydrodynamic pressure, three suitably powered pressure meter probes were fitted on the vertical wall (WIKA model S-11), in three expressly made holes.

Probe signals, after analog-digital conversion, were acquired by an electronic processor of 1000 Hz frequency, achieving a high precision rate in experimental data collection. A high pressure water supply system was also fitted to allow a powerful flush through the pump manifolds in the inlet flexible pipes, in order to remove all possible residual mix.

The experimental installation included two batteries of three pito-meters each, located respectively at the end of the drain and in the mud collecting channel, downstream of the grid. Each pitot pipe was connected in such a way as to avoid any mud consolidation at the end of the test causing obstruction to the meters or clogging.

4. Experimental Results

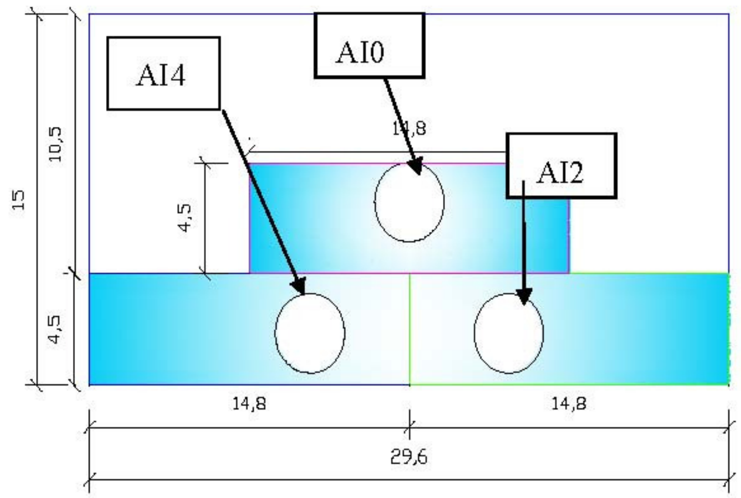
The following tests were carried out on the physical model arranged for this purpose, for the purpose of:

- measuring hydraulic features upstream and downstream of the dissipation device;
- measuring hydrodynamic pressure p_i generated by jet impact on the barrier wall;
- estimation of hydrodynamic boost;
- estimation of the energy impacted on the wall, as ratio of hydrodynamic pressure and Δh working jump (≈1.20 m).

For detection of hydraulic features of the stream flowing into the device, velocity was estimated by Pitot pipes and the estimation of water depth was obtained by a hydrometer.

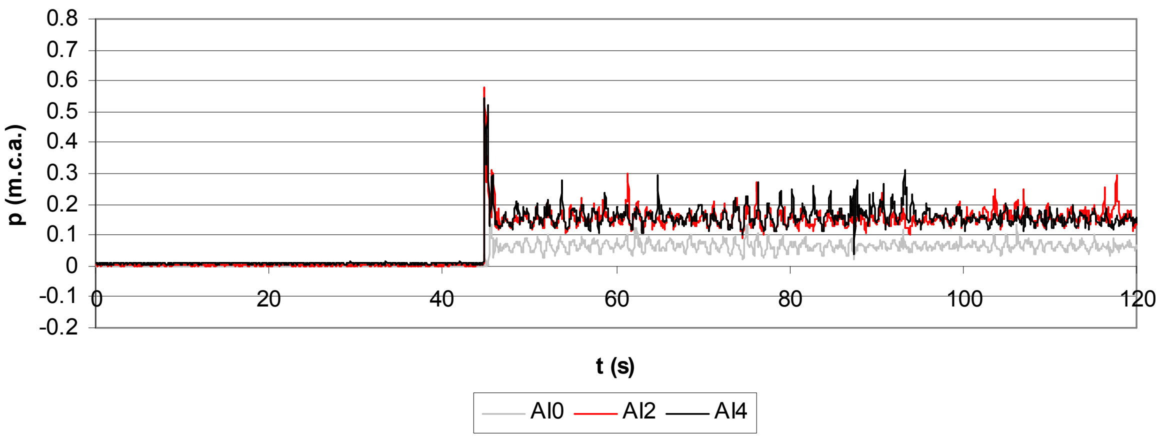
Tests have shown the effective operation as water feed varies, as well as allowed to calculate medium and maximum values of the distribution trend of pressure. Such a trend decreases from the bottom of the wall to the top, with mounting values as the water flow increases. Each test consisted of three different detection positions: two at the bottom of the wall and one at the geometrical barycenter of the wall. The dimensions were 29.6 × 15 cm as shown in Figure 4.

Figure 4. Terminal wall barrier with pressure probes (dimension in cm).



Each test had to last 120 s; some tests lasted up to 300 s without significant differences in the detected data; transducer signals after analog to digital conversion were acquired by an electronic processor with 1000 Hz frequency, providing a high precision rate of experimental track detection. As an example, Figure 5 indicates one of the experimental records for the detected transducers. The graph refers to a test with a discharge of Q = 20 L/s and shows the pressure signal p trend as reported in water column meters and relevant to each channel.

Figure 5. Typical pressure trend detected by the pressure probe *vs*. time.



Since the pressure trend is quite irregular (it should be pointed out that there is also a "noise" caused by vibration of wall structures generated by the jet impact), in order to get more significant indications for each test, it was decided to estimate synthetic parameters capable of characterizing recorded signal trends:

- pressure signal minimum, medium and maximum values;
- pressure signal effective value, as defined by the following ratio:

$$Y_{eff} = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_i - Y_{med}\right)^2}{n-1}} \quad (5)$$

Y_{med} is the average pressure value (in time) while Y_i is the value measured at a generic time of the test.

Average pressure values are lower than maximum values, which are very quick (some milliseconds); it is therefore very difficult to assess how significant they are from a technical perspective.

Average pressure values show approximately the same trend in all tests, with a maximum for the transducers located at the wall bottom (AI4 e AI2 in Figure 4) and decreasing values for the probe located on top of the barrier (AI0). Average pressure values tend to increase when the discharge increases.

Maximum Pressure values distribution shows a maximum at the wall bottom and decreasing values for the transducer located on top of the barrier (AI0, Figure 4).

Effective Pressure values are not totally negligible, even if greatly lower than maximum (they represent an index of stream moving status: high values would mean a possible pulse exaltation and, eventually, the possibility of resonance). (Generally Y_{eff} has values 25 ÷ 40% of corresponding average values in the section detected at the wall base, with a decreasing trend in absolute value from the wall bottom to the top).

This supports previous observations about maximum pressure values: the less significant effective values are, with respect to maximum values reflects, most probably means a lower frequency of pressure maximum peaks, as was shown by test records, one of which is reported in Figure 5.

Concerning dissipation percent with respect to total potential energy, after testing peak pressure on transducer membrane (32 mm diam.), the hypothesis was that its distribution was uniform across the surface around the membrane, which was the same for all three transducers and equals 66.6 cm^2.

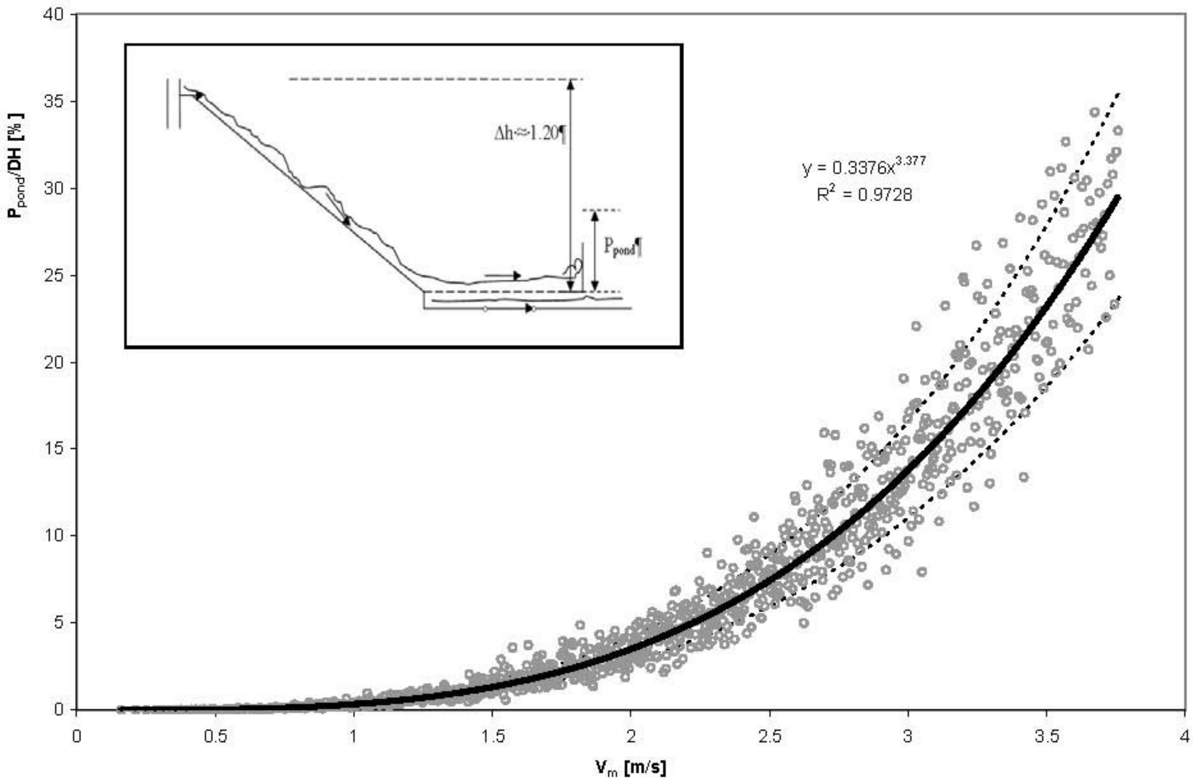
For the three probes the following formula was applied:

$$F_{tp} = \sum_{i=1}^{3} p_i \cdot A_i \quad (6)$$

Strength varies as upstream V_m varies. After the assessment of load pressure with respect to the three transducers, we could calculate energy dissipation near the wall. The ratio was calculated between dissipated energy on the wall ($P_{pond} = F_{tp}/(A_1 + A_2 + A_3)$) and total available potential energy ($\Delta h \approx 1.20$ m). A diagram was made of such percentages as incoming stream average speed varies (Figure 6).

Results analysis (Figure 6) has shown that total dissipation percentage, due to the terminal barrier wall, escalates, as does total hydrodynamic boost as the stream speed increases coming from uphill. Moreover the dissipation maximum value provided by the terminal wall is 35%.

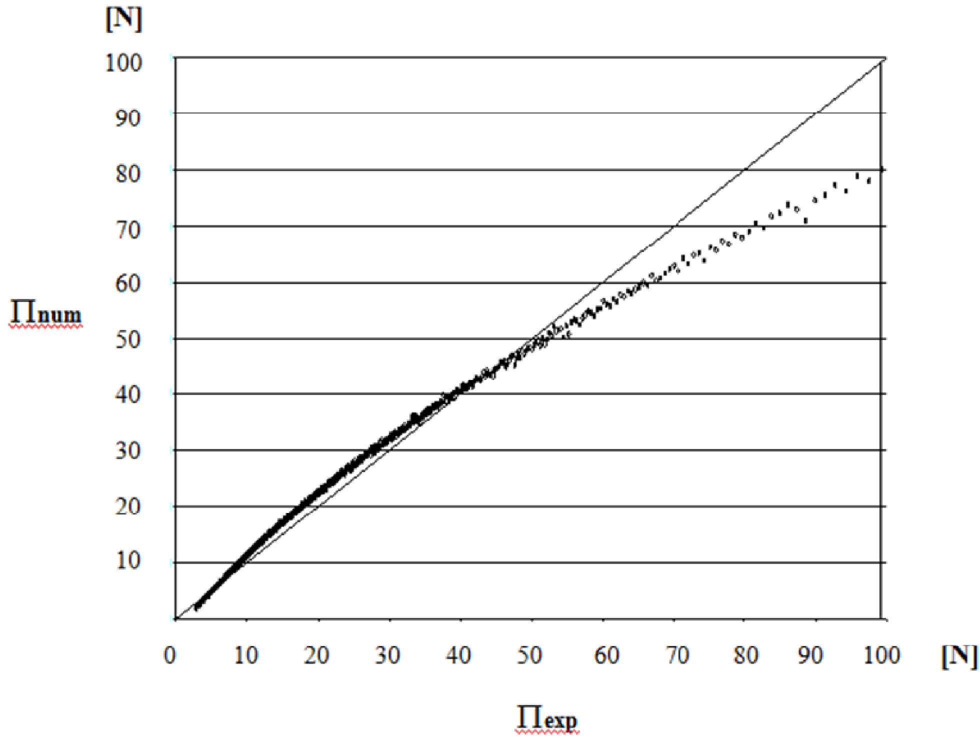
Figure 6. Percentage of total load dissipation *vs*. V_m.



We can conclude that, for lower speeds of incoming stream into the device (1.0 ÷ 2.5 m/s), energy dissipation is only due to the grid (grid effect), while for higher values (2.5 ÷ 3.5 m/s) (Froude densimetric numbers vary in a range of 6–9) also the wall plays a role (wall effect) so that the overlapping of the two effects provides a total dissipation which is significantly higher.

As can be seen in Figure 7, the hydrodynamic drive calculated from the tests was compared with corresponding theoretical model values [formula (3)]. The comparison shows a good match between the calculated formula (3) and experimental results. In particular, we can see that for values lower than 40 N, the theoretical model leads to safe results while higher values of the theoretical model lead to an underestimation of the real boost. This is probably due to the high pressure variability registered during the test.

Figure 7. Comparison of the theoretical formula (3) (∏num) with experimental values (∏exp).



5. Discussion

In the technical literature there are few references about mudflow breakers design criteria. Certain simple criteria were mentioned by [9], concerning some defense structures built in the San Francisco Bay. The authors suggested the construction of breakers composed of small elements of wood, steel or concrete, dimensioned in order 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 resistance to the flow, every single element can be connected to the others by chains or metallic nets. 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 [10]. 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 defense structure. Physical modeling on structural measures against debris flow is not often utilized because of the complexity of their design and the high cost compared to realizing hydraulic models. Nevertheless, nowadays creating such models is recommended for safety reasons as they are at present the most reliable tool in order to verify the effectiveness of such structures. However, the problems which physical modeling incur are not easy to solve and the determination of the proper similarity law is also not a simple task. Scientific literature reports a number of approaches, although a general agreement on all issues is still lacking. Even if debris or mudflow is to be considered an unsteady phenomenon, similarity laws are obtained by general equations relevant to steady one-dimensional flow of a homogeneous fluid, with average density ρ, and to the mass conservation. In contrast, 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 of modeling, 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 insignificant with respect to inertia and gravity, therefore in mudflow modeling 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 (densimetric Froude number, [10]), with C volume concentration of the solid phase, $\Delta = (\rho_s - \rho)/\rho$ relative density of the solid phase and g gravity acceleration (ρ_s solid phase density, ρ water density). In the present study, the weight concentration varies in a range of 30–34%, while the volume concentration C varies in a range of 50–60% and the Froude number densimetric Fr_{dens} varies between 6 and 9.

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.

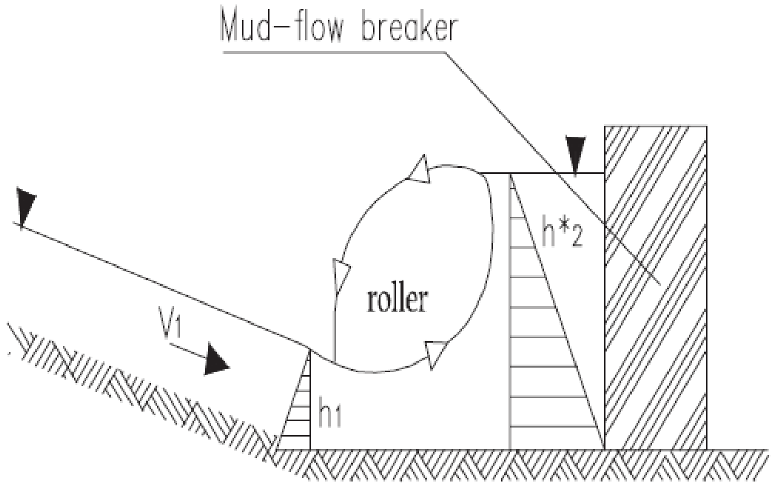
$$\frac{\lambda_\rho \cdot \lambda^{1/2} \cdot \lambda_d}{\lambda_\mu} = 1 \tag{7}$$

Equation (7) indicates that in physical modeling of debris and mudflow it is usually necessary to use a material with a characteristic diameter that is not much reduced in respect to the geometric scale of the model, in order not to avoid too high and unrealistic scale reduction values for λ_μ.

The correct evaluation of the dynamic impact of a mudflow front against a structure is an important task in its design procedure. It is evident that the dynamic impact does not depend solely on the flow depth of the incident front, but depends mostly on its kinetic characteristics. In spite of this, very often in professional practice, the dynamic impact is simply evaluated as the hydrostatic pressure of the incident flow multiplied by an arbitrary coefficient larger than one. If this coefficient is not large enough, the impact force of the debris or mudflow can be dramatically underestimated.

Furthermore, often the hydrostatic pressure is referred to the density of clear water, while the density of a mudflow or of a debris flow can exceed the density of water by a factor of two. Therefore, if the coefficient is taken as smaller than two, the design pressure may be exceeded by the effective hydrostatic load. The dynamic impact observed from the performed tests has shown the classical formation of a roller wave (Figure 8).

Figure 8. Representation of the roller forming upriver with respect to the flow breaker [10].



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 defining the extent of the zone subjected to erosion. For this reason, a simplified approach has been proposed with reference to the rollers. The expression proposed here is:

$$\frac{l_r}{h} = 3.225 \cdot Fr_{dens} - 13.356 \tag{8}$$

with the following limits:

$$\begin{cases} 6 \leq Fr_{dens} \leq 9 \\ \dfrac{h}{b} \leq 0.1 \end{cases}$$

where l_r is the roller length; h the upstream flow depth; Fr_{dens} is the densimetric Froude number of the upstream flow, and b the channel width.

6. Conclusions

The experimental tests were run to assess the amount of dissipation provided to the energy of a mudflow by a vertical barrier wall. An important parameter to be taken into account in mudflow breaker design is the solid concentration. A mudflow, characterized by relatively low values of solid phase concentration, shows generally high velocities and small flow depths in which case the dynamic impact on the blocks can be particularly devastating. On the other side, mudflows with relatively high solid concentrations are characterized by thick flow depths and low flow velocities which may lead to overflow problems. According to the test and to the speed range detected, the maximum dissipation rate due to the wall was about 35% of the available total load.

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