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DYNAMIC IMPACT OF A DEBRIS FLOW FRONT AGAINST A VERTICAL WALL

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ABSTRACT

Recent experimental results obtained at the University of Trento show that a liquid-granular wave can impact against a vertical obstacle producing two different mechanisms of reflection, depending on the Froude number: if the front is sufficiently fast, the flow is completely deviated in the vertical direction, producing a vertical jet-like bulge, while if it is relatively slow it can be totally reflected in direction normal to the obstacle.

The standard theoretical approaches for the analysis of the dynamic impact of a granular front against an obstacle take into account only the second mechanism described above and are obtained from the mass and momentum balances applied to the reflected bore under the hypothesis of homogeneous fluid.

We extend this approach to the case of a two-phase granular-liquid mixture, taking into account the presence of a deposit of granular material near the wall, as observed in the experiments. Furthermore we propose a theoretical analysis of the formation of the vertical bulge, that is usually observed for Froude numbers larger than one, and propose an original analytical expression to estimate the dynamic impact forces also in this situation.The theoretical approaches we propose are suitable to describe the experimental results with a reasonable agreement.

Key words: *dynamic impact, debris flow, vertical wall, Froude number*

INTRODUCTION

The correct estimation of the dynamic impact of a debris flow front against a structure is a key phase of its design procedure. It is evident that the dynamic impact does not depend solely on the flow depth of the incident front, but it depends mostly on its kinetic characteristics. In spite of this, very often in the professional praxis 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 mud flow can be dramatically underestimated. Besides often the hydrostatic pressure is referred to the density of the clear water, while the density of a mudflow or of a debris flow can exceed by a factor of two the density of water. Therefore, if the coefficient is taken smaller than two, the design pressure may be even exceeded by the effective hydrostatic load, which is clearly a wrong assumption. In more favourable cases the impact force is evaluated invoking a homogeneous fluid scheme accounting for the formation of a completely reflected wave (Fig. 1), as proposed by Zanuttigh & Lamberti (2006), but we will show in what follows that also this approach may lead to the underestimation of the correct impact force

In fact the dynamic impact of a fluid surge against a vertical wall can occur according to two different mechanisms (Armanini & Scotton, 1993; Armanini, 1997): with the formation of a completely reflected wave or with the formation of a vertical bulge (Fig. 1). In the first case, after the impact a reflected wave is formed, propagating upstream with a celerity a, which can be assumed constant at least nearby the wall. In the second case, the flux is deviated upwards parallelly to the vertical wall, with the subsequent formation of a falling jet and then of a hydraulic jump that propagates upstream.

We will show in this paper that the Froude number of the incoming surge plays an important role in the determination of the impact mechanism. When gravity prevails over inertia, typically there is the formation of a reflected wave

On the contrary, when inertia prevails there is the formation of a vertical bulge. In this second mechanism, the maximum pressures occur before the formation of the hydraulic jump, that is before the beginning of the energy dissipation. Each mechanism can take place both when the fluid is homogeneous and when it is composed of two phases, e.g. a granular matrix suspended in a liquid. In the first part of the present paper we consider the flow of a homogeneous fluid and evaluate the impact force when the formation of a vertical jet is observed after the collision. In the second part of the paper, we introduce a two-phase approach. The theory was verified by means of appositely designed experiments carried out at the University ofTrento.

EXPERIMENTAL SETUP AND METHODS

The experiments were carried out in a 3.86 m long flume (Fig. 2) with a 25.2 cm wide rectangular cross-section, closed at the downstream end with a vertical wall equipped with four piezoresistive pressure gauges, positioned as depicted in Fig. 3.

Two supplementary pressure gauges were placed at the bed of the flume, just upstream of the vertical wall. In the upstream part the flume was equipped with a removable gate, used to create a reservoir that can be suddenly opened for the generation of a steep wave. The experiments were carried out in a range of slopes between 0 and 44%.

The experiments were filmed by means of two synchronized high speed CCD cameras at a frame rate of 500 frames per second and a pixel array of 1024 x 1024. The image sequences acquired with the two cameras were synchronized also with the output of the 6 pressure gauges mentioned above.

The images were analyzed by means of imaging techniques developed appositely for the study of granular flows (Capart *et alii*, 2002; Spinewine *et alii*. 2003). The fluid was seeded with tracers and one example for the results of the particle identification process is depicted in Fig. 4, were an original image and a filtered image with indication of the estimated particle

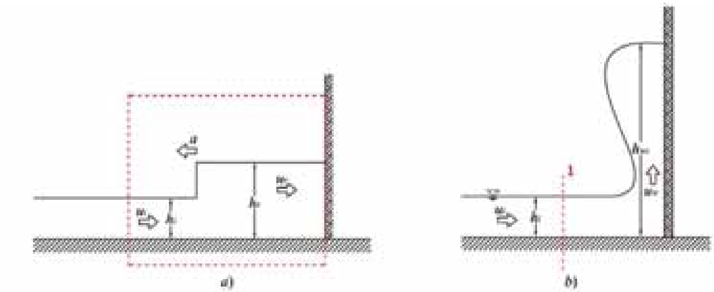

Fig. 1 - Possible schemes of reflection of a debris flow front against a vertical wall according to the homogeneous fluid case and control volumes utilized for the mass and momentum balance; a) formation of a completely reflected wave; b) formation of a vertical jet

Fig. 2 - Experimental flume used for the experiments

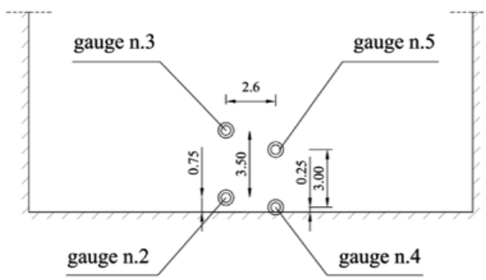

Fig. 3 - Scheme of the position of the pressure gauges on the vertical wall at the downstream end of the flume (distances expressed in cm)

positions is shown.

In the present paper the imaging techniques were utilized to derive the flow kinematics and the particle trajectories, utilized for the interpretation of the various possible impact schemes. A graphical example of this type of analysis is given in Figure 4

HOMOGENEOUS FLUID SCHEME WITH FORMATION OF A COMPLETELY REFLECTED WAVE

We first consider a simplified homogeneous fluid scheme with formation of a completely reflected wave. Assuming a control volume translating upstream with the reflected wave, as presented in Fig. 1a, the mass and momentum balances of a homogenous mixture of density ρm lead to the following expressions:

$$\begin{aligned} &\rho_m(a+u_r)h_r = \rho_m(a+u_i)h_i \\ &\frac{1}{2}g\rho_m\left(h_i^2-h_r^2\right) = \rho_m(a+u_r)^2 h_r - \rho_m(a+u_i)^2 h_i \end{aligned} \qquad (1)$$

where h_r and h_i are the depths of the reflected and incident wave and u_r and u_i are the respective flow velocities. Wall friction and gravity are negligible in the momentum balance. At the moment of the impact the velocity on the wall is zero, that is $u_r = 0$. In this hypothesis the system becomes:

$$(Y^2-1)(Y-1) = 2YF_{ri}^2 \qquad (2)$$

where $Y = h_r / h_i$ is the ratio between the flow depths and $Fr_i = u_i / (gh_i)^{1/2}$ is the Froude number of the incident wave.

An approximated solution for equation (2) was proposed by Armanini (2009):

$$Y \cong \left(1+1.51F_{ri}^{1.2}\right)^{5/6} \qquad (3)$$

Under the hypothesis of hydrostatic pressure distribution, using eq. (3), the impact force $F = 1/2(g_\rho m h_r{}^2)$ on the vertical wall can be evaluated in dimensionless form, **F**, respect to the hydrostatic force of the incident front under the hypothesis that at the impact the pressure distribution on the wall is hydrostatic.

$$\tilde{\mathbf{F}} = \frac{1/2(g\rho_m h_r^2)}{1/2(g\rho_m h_i^2)} = \frac{\mathrm{F}}{1/2(g\rho_m h_i^2)} = Y^2 \cong \left(1+1.51F_{ri}^{1.2}\right)^{5/3} \qquad (4)$$

The above scheme is valid also for a reflected wave of finite height. In this case however the mechanical energy is not conserved.

HOMOGENEOUS FLUID SCHEME WITH FORMATION OF A VERTICAL JET

When the Froude number of the incident wave exceeds unity, the impact mechanism consists in the formation of a vertical bulge (Fig. 1b). The largest pressure peaks on the vertical wall develop before the formation of the falling jet and its consequent breaking associated with energy dissipation (Fig. 5).

Before these dissipative phenomena take place and, therefore, until the jet reaches the maximum height h_{ro}, corresponding to a raising velocity $u_{wo} = 0$, energy conservation (ideal fluid approximation) can be assumed along the streamlines. The application of the

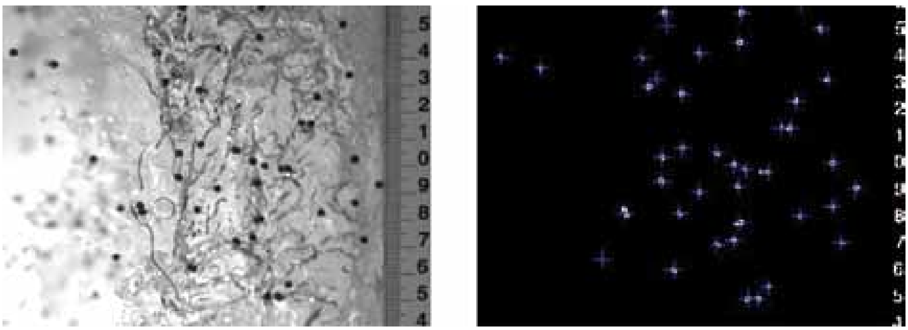

Fig. 4 - Example of results of the particle tracking procedure: the fluid is seeded with tracers, that are identified and tracked using particle tracking methods based on the Voronoï polygons (Capart et alii, 2002; Spinewine et alii, 2003)

reflected-wave scheme in such a situation would lead to an underestimation of the pressures at the moment of impact, as showed in Fig. 6.

In a first approximation, we have neglected the time variation of the velocity in the balance or, equivalently, we assumed as valid the Bernoulli theorem:

$$h_i + \frac{u_i^2}{2g} = h_w + \frac{p_w}{\rho_m g} + \frac{u_w^2}{2g} \tag{5}$$

where hw, pw and uw represent the distance from the bed, the pressure and the velocity relevant to a generic point along the wall (Fig. 1b). We indicate with hwo the distance of the top of the jet from the bed, and with $(h_{wo})_{max}$ its maximum value. At the moment of maximum height of the jet, in equation (5) we have $u_w = 0$. Assuming the hydrostatic pressure distribution on the vertical wall, the dimensionless maximum impact force F ~ results to be:

$$\widetilde{\mathbf{F}} = \frac{1/2(g\rho_m (h_{wo})_{max}^2)}{1/2(g\rho_m h_i^2)} = \left(1 + \frac{1}{2} F_{ri}^2\right)^2 \tag{6}$$

where $(h_{wo})_{max}$ is the maximum height of the jet, evaluated by means of the energy balance (eq. 5), in which we put $h_w = h_{wo}$, $p_w = 0$ and uw = 0, leading to $h_{wo}/h_i = 1 + 0.5F^2_{ri}$.

the comparison (Fig. 6) of the dimensionless impact force determined by the two mechanisms shows that the formation of a vertical bulge determinates a larger force, that become significant for Froude numbers larger than 3.

In our experiments we did not measure the forces, but just the pressures at some points on the wall (Fig. 2b). The experiments showed (Fig. 7) impact pressures larger than that corresponding to the hydrostatic distribution (hypothesis utilized to obtain equation 6). Besides, in order to derive equation (6) we applied the Bernoulli theorem assuming a stationary flow condition. This is just a rough approximation because the inertial term is presumably important in the phenomenon that we are describing. However, we can estimate the time-derivative of the velocity on the base of a scale analysis. In fact, during the phenomenon the velocity decreases from u_i, at the incident front, to zero, at the moment when the

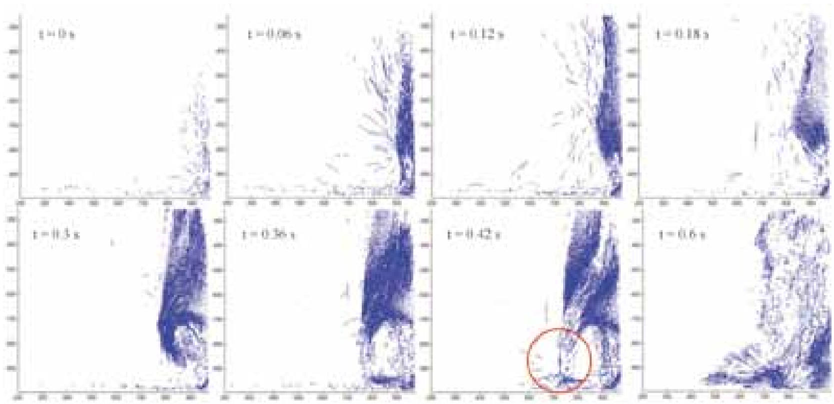

Fig. 5 - Particle trajectories at different time steps, expressed in seconds, obtained applying the imaging methods to an experimental run with the formation of the vertical jet. The circle in the seventh panel gives evidence to the breaking of the jet on the free surface of the incoming flow

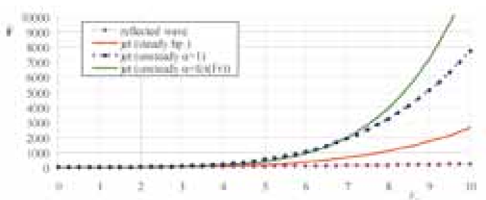

Fig. 6 - Impact force as a function of the Froude number of the incident wave obtained for a homogeneous fluid using the reflected-wave theory and the vertical-jet theory. The parameter α is introduced in equation (7) to take into account non-stationary phenomena

maximum height of the jet is reached, that is u_i can be considered the time scale of the phenomenon. In a first order approximation, the time dependent term in the momentum balance can be therefore estimate to be proportional to ρu_i^2 through a constant α.

In this way eq. (5) is improved, accounting in an approximate form for the variation of the velocity vector, leading to:

$$h_i + \frac{u_i^2}{2g} = h_w + \frac{p_w}{\rho_m g} - \alpha \frac{u_i^2}{2g} \qquad (7)$$

However, α is an unknown parameter and needs to be estimated in order to make use of equation (7) as a design tool.

A scheme of the picture given above is represented in Fig. 8 andFig. 9, where it is shown how the measured pressure exceeds the hydrostatic pressure close to the bottom, where the maximum impact is observed, while the effective pressure is smaller than the hydrostatic one at the top, where nevertheless the countermeasures do not usually present particular static problems caused by the impact of a steep wave.

From Fig. 7 we observe that α is not constant. Equation (6) underestimates systematically the measurements, especially in the case of gauges n. 4 and n. 2, that are closer to the bed. The estimate relevant to the higher gauges is more favourable since the partial detachment of the jet from the wall, which takes place when it approaches its maximum elevation, induces a reduction of the measured pressures

The results presented in Fig. 7 can be used to calibrate the coefficient α in order to correct the

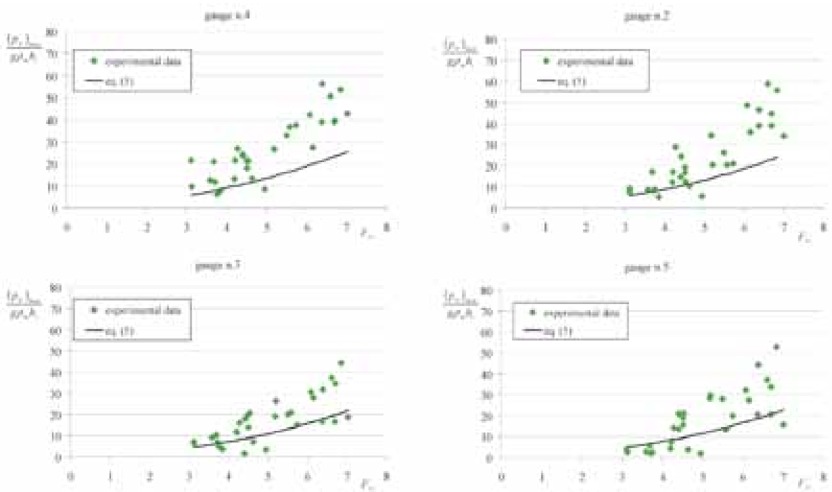

Fig. 7 - Experimental dimensionless maximum pressures compared with the theoretical expression. Equation (6) underestimates systematically the measurements, especially in the case of gauges n. 4 and n. 2, that are closer to the bed

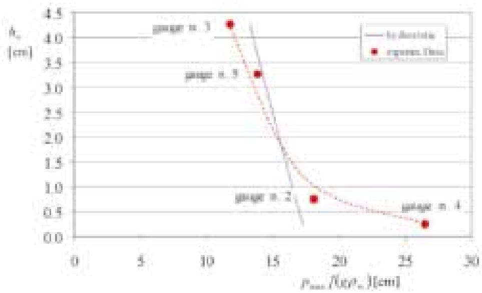

Fig. 8 - Peak pressures measured with the pressure gauges on the vertical wall (dashed red line) compared with the hydrostatic pressure distribution (solid black line)

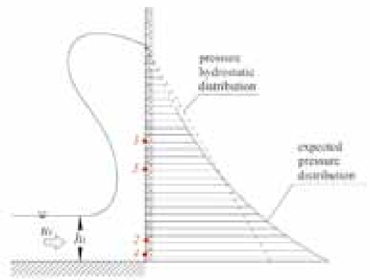

Fig. 9 - Scheme of the jet and of the measured pressure distributions at the maximum height of the vertical jet

estimation of the impact pressures. Fig. 10 depicts the behavior of α as a function of Froude number of the incident wave in the different gauges. The figure shows that α increases as the Froude number increases, up to values of $\alpha \approx 1$. As a consequence we may argue that for design purposes it is precautionary to evaluate the impact force utilizing $\alpha = 1$.

Starting from equation (7) and making the same assumptions introduced for obtaining equation (6) from equation (5), it is possible to express a new formulation for the impact force:

$$\widetilde{\mathbf{F}} = \frac{1/2(g\rho_m h_{ro}^2)+\alpha\rho_m u_i^2 h_{ro}}{1/2(g\rho_m h_i^2)} = \left(1+\frac{1}{2}F_{ri}^2\right)\left(1+\frac{\alpha F_{ri}^2}{1+1/2\,F_{ri}^2}\right) \quad (8)$$

Equation (8) improves the estimation of the impact force given by equation (6), which could underestimate the effective impact especially for large Froude numbers of the incident flow. It should be noted that equations (6) and (8) coincide if $\alpha = 0$ and that the magnitude of the correction increases as the Froude number increase.

TWO-PHASE SCHEME

Actually debris flows consist of a mixture of water and sediments and in many cases the homogeneous fluid scheme represents a too strong idealization. If the size of sediments is relatively large and the volume concentration of the granular phase is big enough, as it is often observed, the homogeneous fluid scheme presented above does not reproduce correctly what happens during the impact of the front against a vertical obstacle. In fact the time scale ruling the segregation between the water and the solids and the time scale of the impact phenomenon may have the same order of magnitude and therefore a static deposit of solid material may develop upstream of the wall.

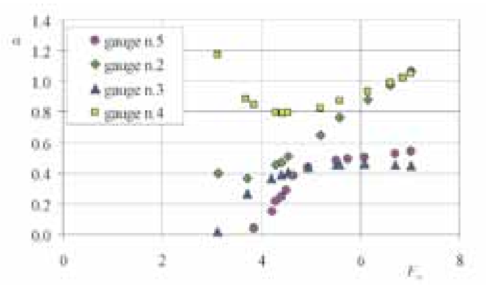

Fig. 10 - Experimental calibration of coefficient α in the case of a clear water steep wave

The experimental analysis has shown that also in presence of two phase flow the two schemes of impact occur. The experiments showed, in fact, that the reflection of the wave takes place with the formation of a completely reflected wave for Froude numbers roughly smaller than unity (Fig. 11), while for faster flows the impact is generally followed by the formation of a vertical jet (Fig. 12).

In the first case the flow is proximity of the wall is substantially different than that of pure water, because a static deposit of solid material is generated upstream of the wall with a repose concentration C_*. The deposit propagates upstream at a constant thickness z_0 with the same celerity a of the reflected wave (Fig. 11). The flow depth, the velocity and the granular concentration of the reflected wave are represented with the symbols h_r, u_r

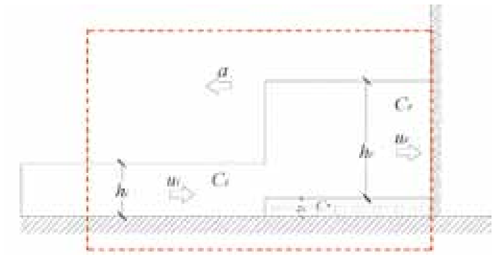

Fig.11 - Possible mechanism of reflection of a debris flow front against a vertical wall according to the two-phase scheme and control volume utilized for the mass and momentum balance in the case of formation of a completely reflected wave

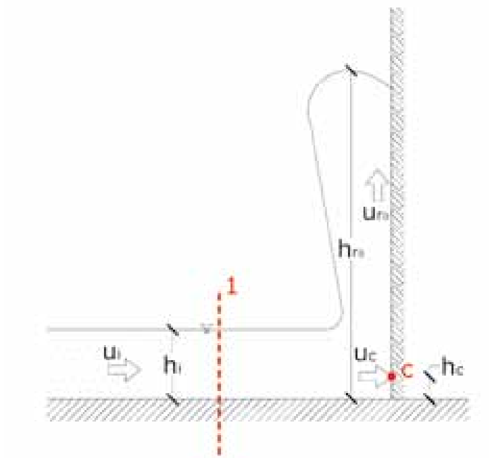

Fig.12 - Possible mechanism of reflection of a debris flow front against a vertical wall according to the two-phase scheme in the case of formation of a vertical jet

and C_r. It should be noted that on the deposit the flow takes place in mobile bed conditions, with a velocity profile that is less uniform than on a rigid bed (Armanini *et alii*, 2005; Larcher *et alii*, 2007; Fraccarollo *et alii,* 2008; Armanini *et alii*, 2009).

From a mass and momentum balance applied to the control volume represented on Fig. 11 and assuming that $u_r = 0$ and $C_r = 0$ at the impact moment, it is possible to obtain an expression for the non-dimensional impact force, similarly to what obtained for the homogeneous fluid case.

On the contrary, in case of vertical jet we have not observed any deposit during the first stage of the impact, during which the maximum of the action against the wall occurs. In this case, the same approach of the pure water can be applied to the two phase flow.

In case of reflected wave, the incident flow is supposed to move at a constant velocity ui and with a constant depth h_i, with a solid concentration C_i assumed to be constant throughout the flow depth

$$\tilde{\mathbf{F}} = \frac{\mathrm{F}}{1/2\, g\rho h_i^2 (1+\Delta C_i)} = \frac{1}{(1+\Delta C_i)} Y^2\left[1+\Delta C_*(1-R)^2\right] = Y^2\left(1 - R\frac{\Delta C_*(1-R)}{1+\Delta C_*(1-R)}\right) \qquad (9)$$

where

$$\begin{aligned} R &= (C_* - C_i)/C_* \\ Y &= h_r / Rh_i \\ Fr_i &= u_i / \sqrt{gh_i} \\ \Delta &= (\rho_s - \rho)/\rho \\ C_R &= (1+\Delta C_i) \Big/ \left(1+\Delta \frac{C_i^2}{C_*}\right) \end{aligned} \qquad (10)$$

and

$$\begin{aligned} a &= u_i \frac{1}{Y-1} \\ z_0 &= h_r \frac{1-R}{R} \end{aligned} \qquad (11)$$

For incident waves characterized by a Froude number larger than one, the formation of a vertical bulge is generally observed. In this case the phenomenon does not show segregation between liquid and solids and the impact dynamics resemble the homogeneous fluid case. The impact force can therefore be evaluated using the same method presented above, if the density of the mixture ρm is used instead of the den-

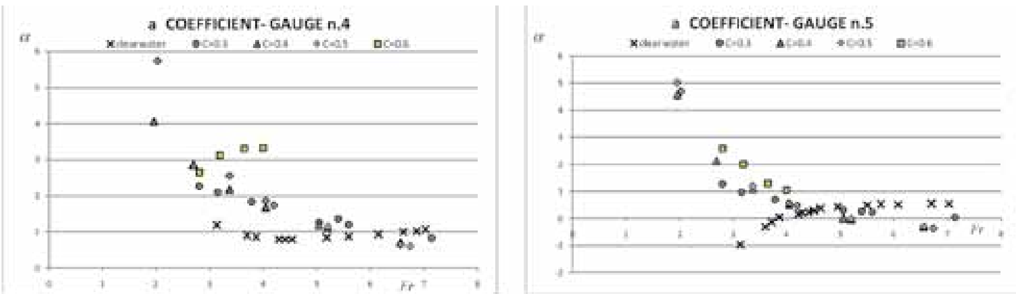

Fig. 13 - Experimental calibration of coefficient α in the case of a two-phase wave on a smooth bed for gauges n. 4 and n. 2

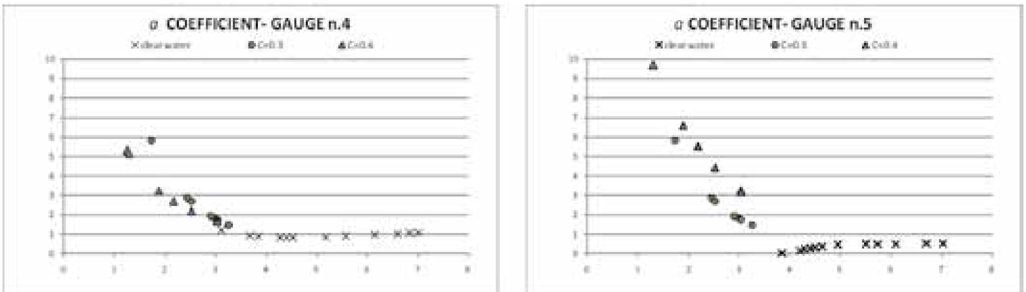

Fig. 14 - Experimental calibration of coefficient α in the case of a two-phase wave on a rough bed for gauges n. 4 and n. 2

sity of clear water ρ.

$$\rho_m = \rho + (\rho_s - \rho)C_i = \rho(1 + \Delta C_i) \qquad (12)$$

$$\widetilde{\mathbf{F}} = \frac{1/2(g\rho_m h_{ro}^2)}{1/2(g\rho h_i^2)} = (1 + \Delta C_i)\left(1 + \frac{1}{2}F_{ri}^2\right)^2 \qquad (13)$$

Also in this case, we have neglected the time variation of the velocity in the balance or, equivalently, we assumed as valid the Bernoulli theorem and, as a consequence, the experimental results were underestimated by the theoretical expression. Applying the same procedure obtained to derive equation (8), equation (13) can be corrected as follows:

$$\widetilde{\mathbf{F}} = \frac{1/2(g\rho_m h_{ro}^2) + \alpha\rho_m u_i^2 h_{ro}}{1/2(g\rho_m h_i^2)} = \left(1 + \frac{1}{2}F_{ri}^2\right)\left(1 + \frac{\alpha F_{ri}^2}{1 + 1/2\,F_{ri}^2}\right) \qquad (14)$$

However in this case we obtained values of the adjusting parameter α that in some cases may be one order of magnitude larger than what obtained for the homogeneous fluid case (Fig. 13 and Fig. 14). Probably this is partially due to the collision of isolated grains against the pressure gauges, however this aspect will beobject of future investigations

CONCLUDING REMARKS

We presented a scheme for the estimation of the impact force of a steep wave against a vertical wall, which is a key phase of the design procedure of hydraulic countermeasures. We showed that the approaches commonly used in the design praxis may lead to a significant underestimation of the impact and that the new scheme we propose in this paper can overcome this problem. Our simpler scheme is based on the hypothesis of homogeneous fluid, but in fact, it can be easily extended to two-phase flows. In some experiments done with granular wet material we observed that in some conditions a deposit may form and propagate in upstream direction after the impact of a debris flow against an obstacle. We showed that to treat this problem properly the hypothesis of homogeneous fluid should be removed.

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